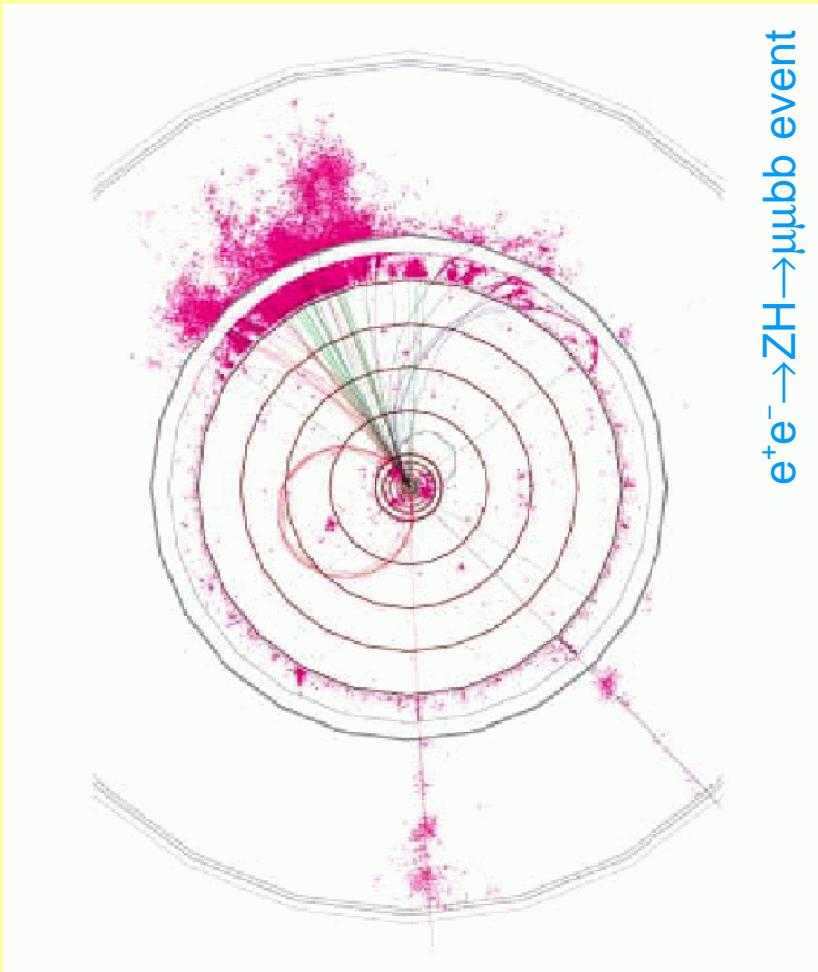


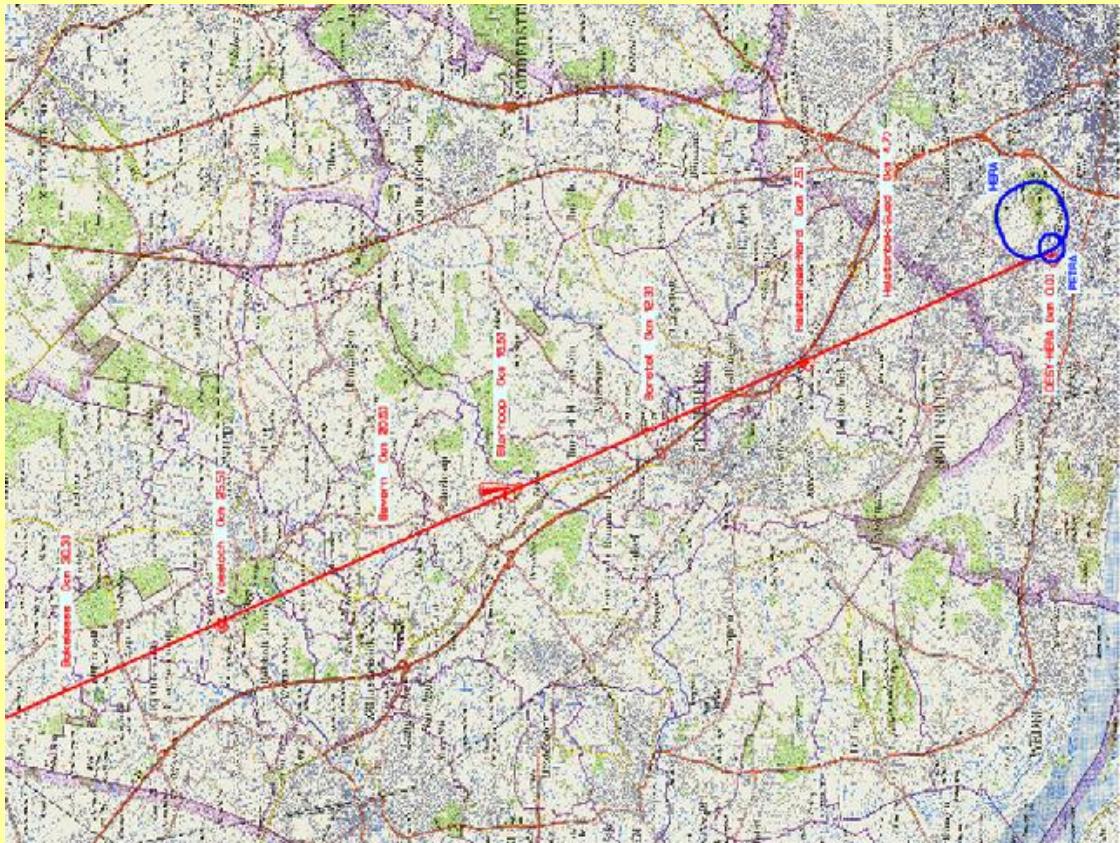
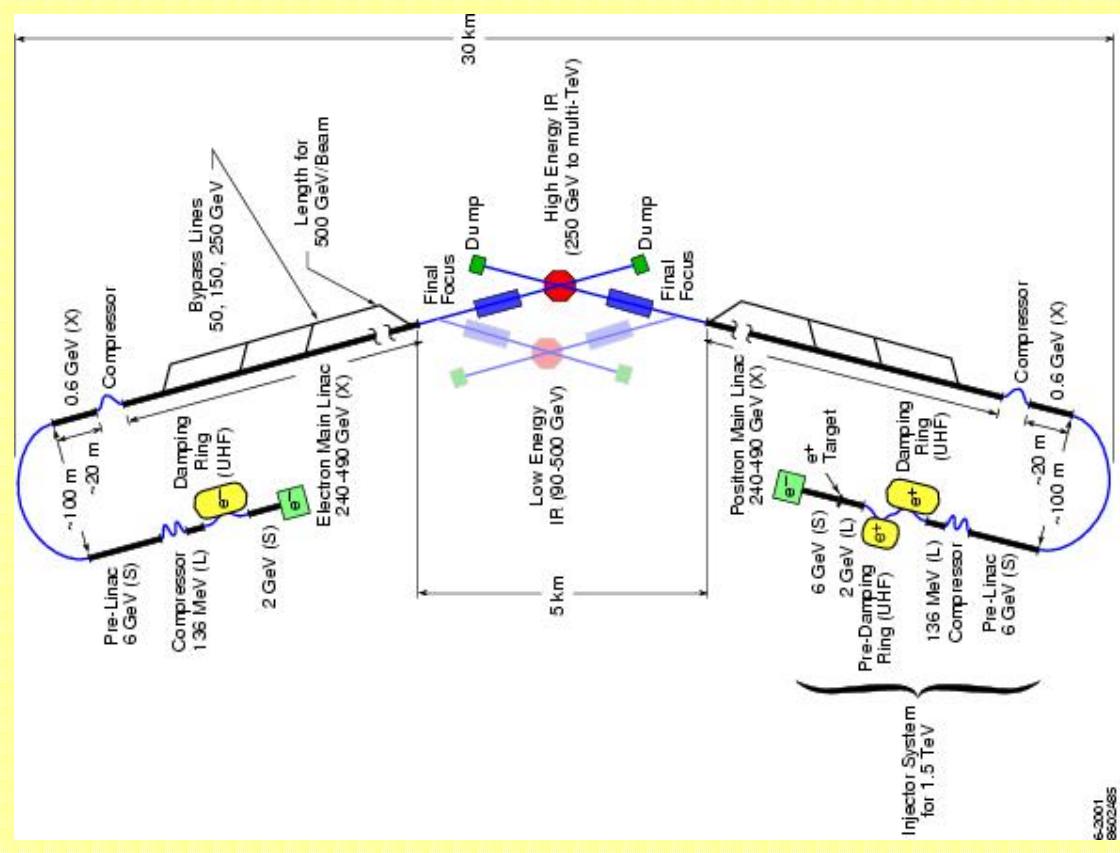
Detectors at the Linear Collider



$e^+e^- \rightarrow ZH \rightarrow \mu\mu b\bar{b}$ event

David Gerdes
University of Michigan
March 26, 2002

Linear Collider Overview



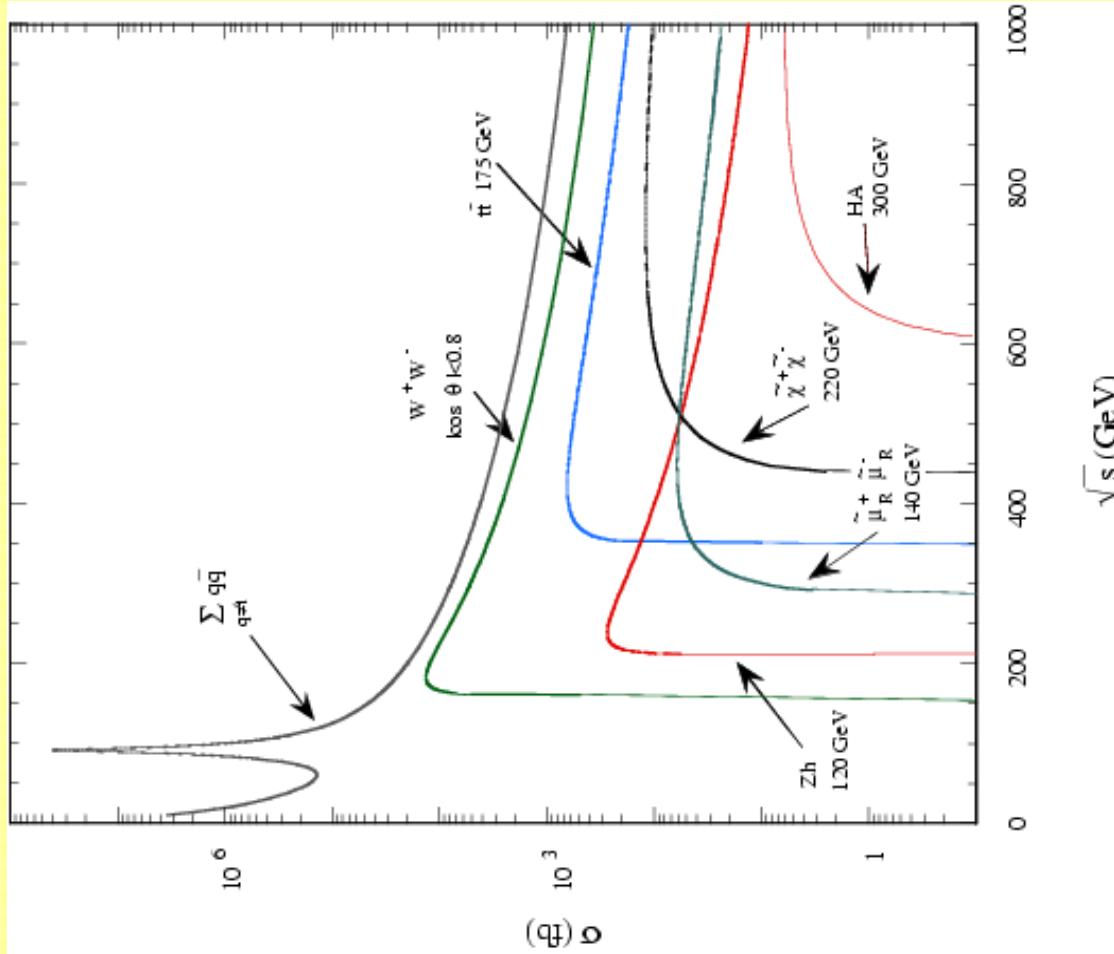
Machine Parameters

	TESLA(500)	TESLA(800)	NLC(500)	NLC(1000)	Tevatron
E (GeV)	500	800	500	1000	2000
Lum. x 1E33	31	5	20	34	0.1
Rep rate (Hz)	5	3	120	120	—
Bunches/pulse	2820	4500	190	190	—
Bunch sep (ns)	337	189	1.4	1.4	396
$\sigma(x)$ at i.p.	553 nm	391 nm	245 nm	190 nm	$30 \mu\text{m}$
$\sigma(y)$ at i.p.	5 nm	2 nm	2.7 nm	2.1	$30 \mu\text{m}$
$\sigma(z)$ at i.p.	0.4 mm	0.3 mm	110 nm	110 nm	30 cm
$\delta B(\%)$	3.3	4.7	4.7	10.2	0
P(e-) (%)	80–90	80–90	80–90	80–90	—
P(e+) (%)	60	—	—	—	—

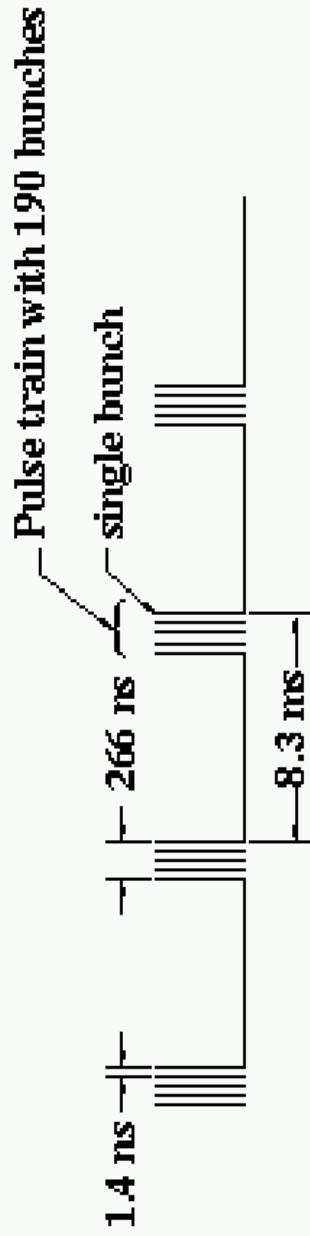
NB: Total cross section:
 ~5 pb (e^+e^- , 500 GeV)
 ~50 mb (p-pbar, 2 TeV)

e^+e^- Cross Sections

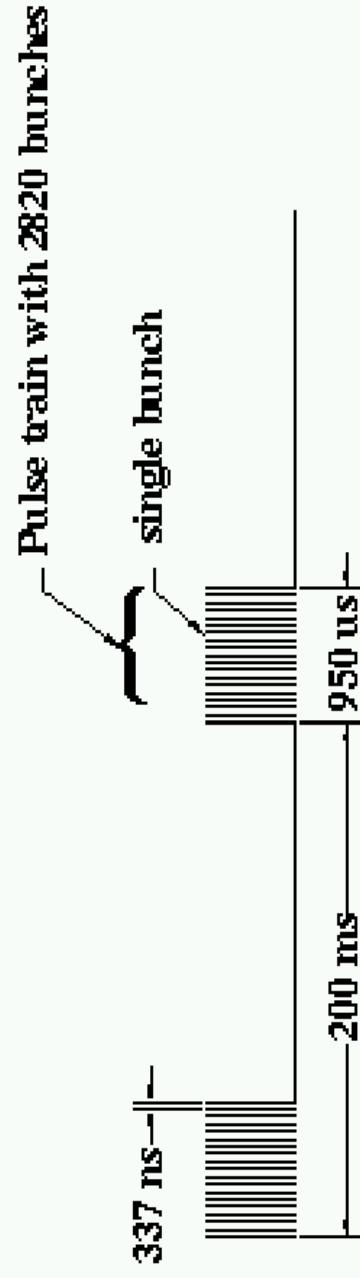
Objects with electroweak
couplings are produced
"democratically"



Bunch structure



a. NLC/JLC 120 pulse trains/sec



b. TESLA 5 pulse trains/sec

Low rates \Rightarrow Read out between crossings
and "trigger" in software

The Challenge of LC detectors?

- Typical Tevatron experimentalist's view:
 - "It's trivial!"
 - "Just copy a LEP detector or SLD!"
 - Sure, the issues of trigger/DAQ appear straightforward.
 - But the challenge is to build a high-precision instrument capable of producing the "textbook data on the next energy scale" (M. Peskin)

Physics Unique to the LC

- Measurement of Higgs branching ratios, e.g.
via $e^+e^- \rightarrow Z h$ followed by $Z \rightarrow ll$, $h \rightarrow X$
- Study of the top quark threshold,
measurements of m_t , Γ_t , α_s , $g_{t\bar{t}h}$
- Precision SUSY spectroscopy
- $t\bar{t}h$ production; top–Higgs Yukawa coupling
- Trilinear Higgs coupling; reconstruction of the
Higgs potential.

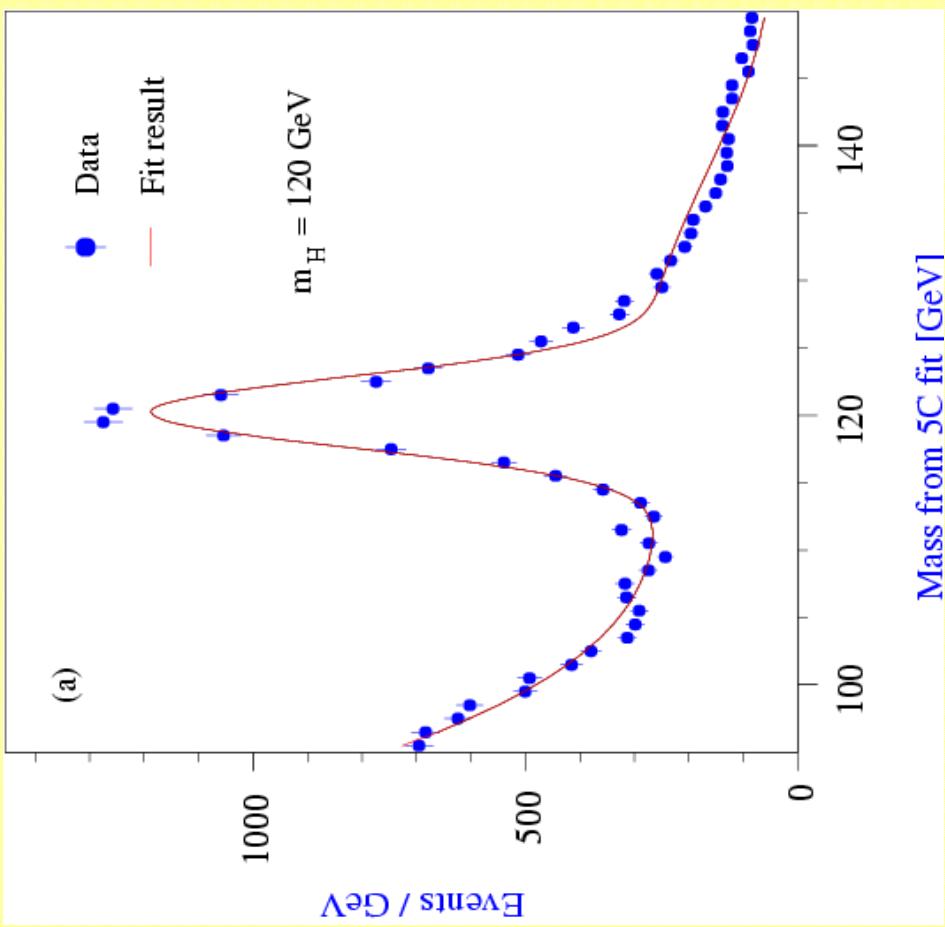
Higgs Reconstruction

- Current EWK fits favor a light Higgs, $m_h < 200$ GeV
- Produced at the LC in recoil off the Z



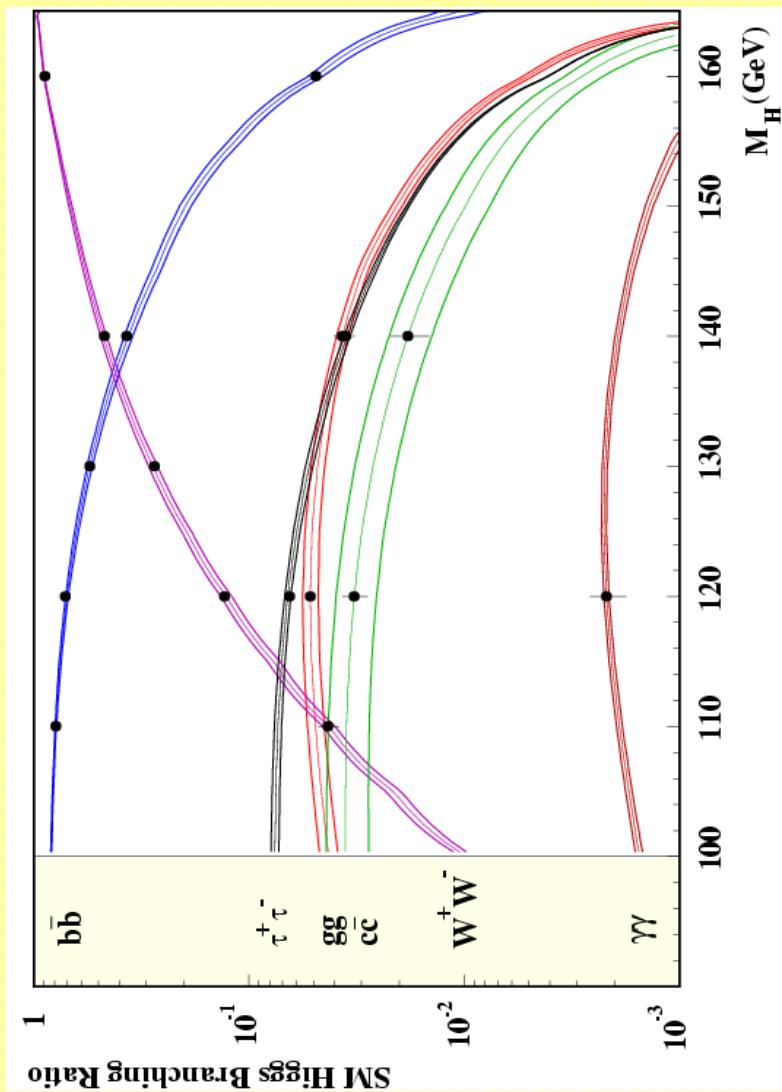
Detector requirement:

Excellent tracking resolution,
 $\sigma(1/p_T) \sim 5 \times 10^{-5} \text{ GeV}^{-1}$



Measurement Of Higgs BR's

- Event selection is based on the Z , not the H , so the Higgs decays constitute an unbiased, inclusive sample.
- Key to determining that "the Higgs is the Higgs"—or something else!



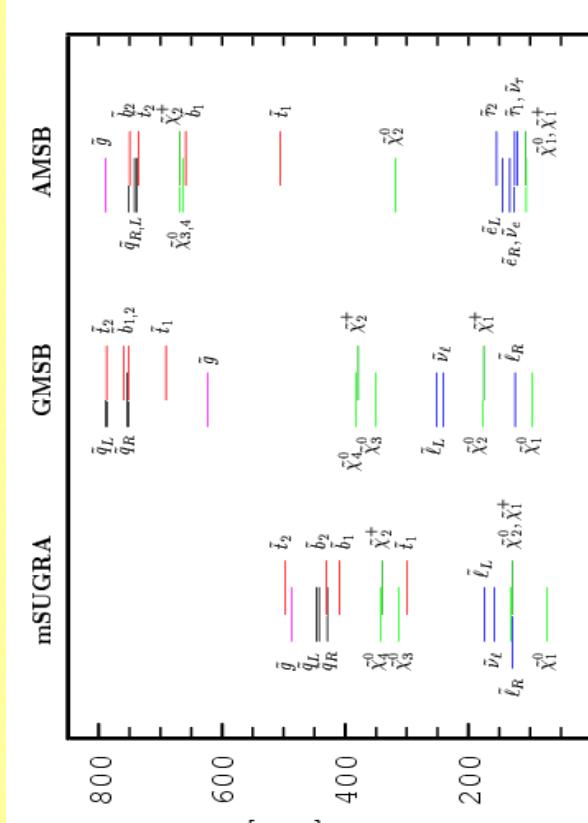
- Detector requirements:
precision vertexing,
flavor tagging.

M. Battaglia

SUSY Spectroscopy

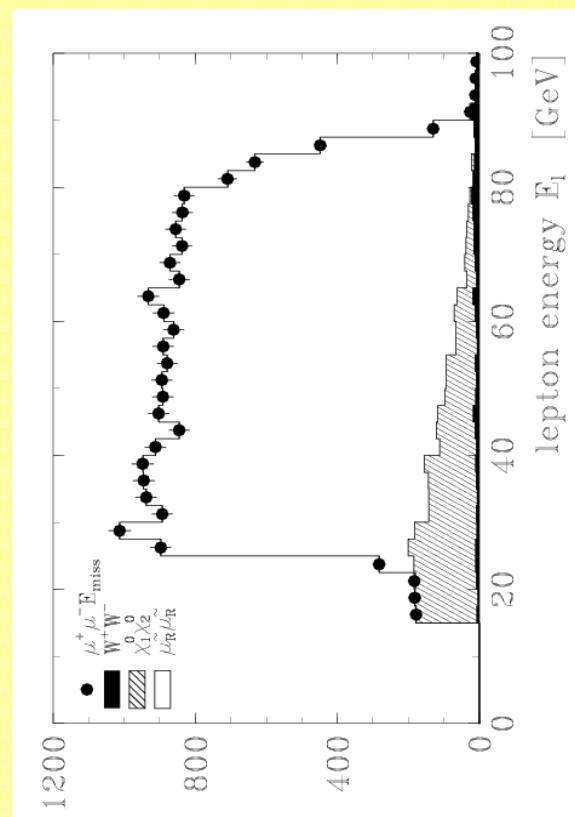
- Pattern of sparticle masses encodes info about SUSY-breaking.

■ Example: endpoints of muon energy spectrum in
 $e^+e^- \rightarrow \mu_L \mu_L \rightarrow \mu^+\mu^- \chi_L^0 \chi_L^0$



Detector requirements:

- Excellent resolution
 - Hermeticity
- Accelerator requirements:
- Ability to vary energy over wide dynamic range
 - Adjustable beam polarization

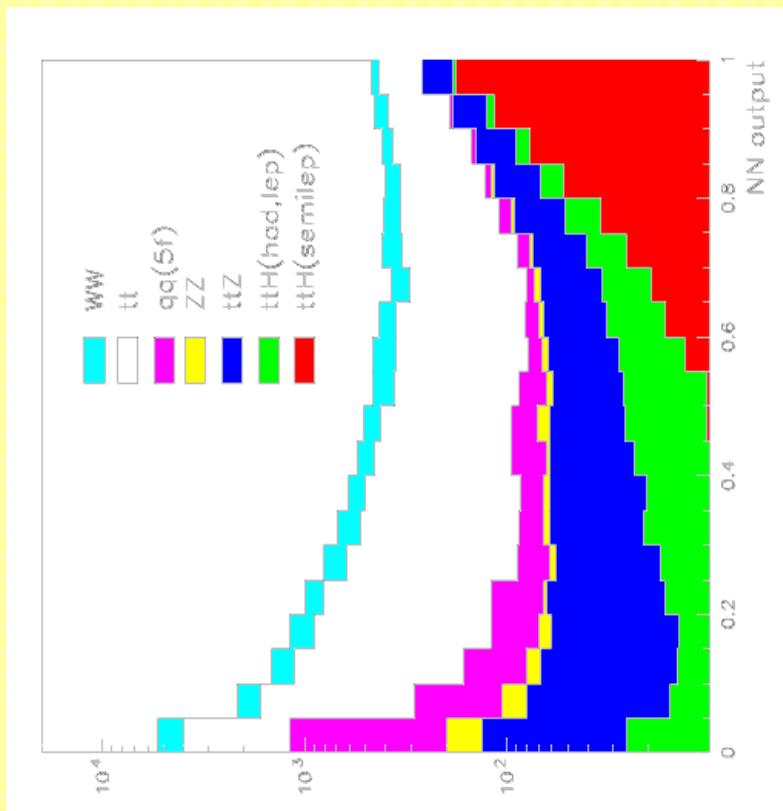


tth production and the Top Yukawa Coupling

- $e^+e^- \rightarrow tth \rightarrow WbWb bb$
- Very complicated final state:
 - Up to 8 jets
 - 4 b's
 - Many kinematic constraints
 - Tiny cross section ($\sim 2 \text{ fb}$), with backgrounds ~ 3 orders of magnitude higher.

- Detector requirements:
 - Excellent jet resolution
 - Flavor tagging

Note: tth cross section maximized at $\sqrt{s} \sim 800 \text{ GeV}$



Juste, Merino: hep-ph/9910301

Reconstructing the Higgs Potential

Physical basis of EWSB: nonzero minimum of the Higgs potential,

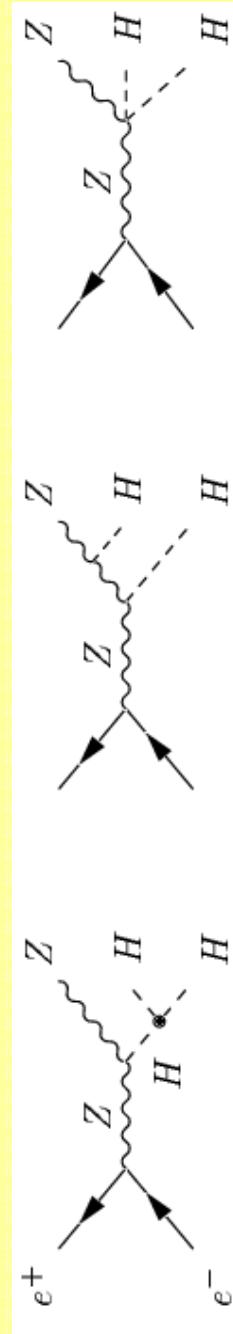
$$\begin{aligned} V &= \lambda(|\phi|^2 - \frac{1}{2}v^2)^2 \\ &\rightarrow \lambda v^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4, \end{aligned}$$

where $v=246$ GeV.

- Measure coefficient of the quadratic term by measuring the mass,

$$M_h^2 = 2\lambda v^2$$

- Measure the trilinear self-coupling via Higgs pair production, $e^+e^- \rightarrow ZHH$

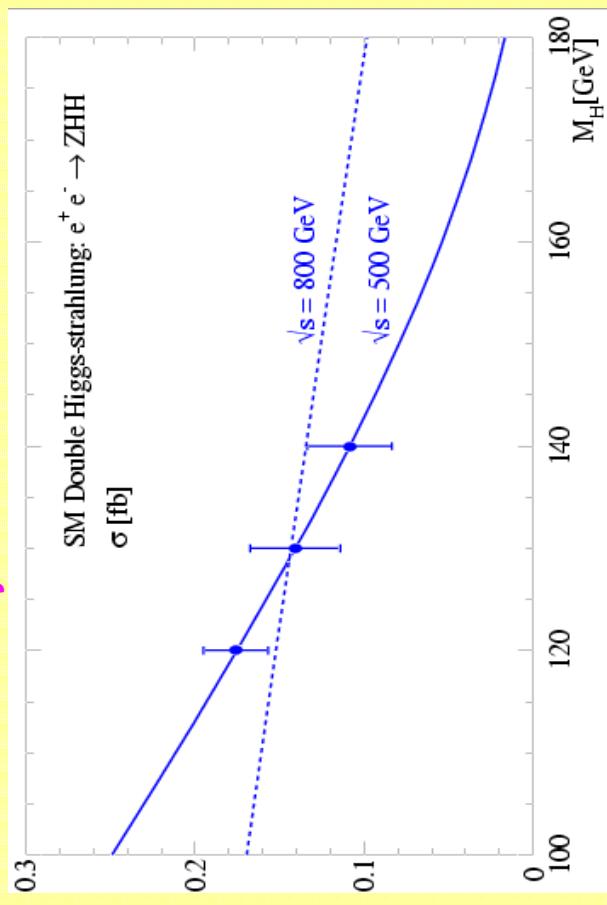


Reconstructing the Higgs Potential

Striking final state: 4 b jets, plus dileptons, jets, or missing energy from the Z decay.

But: Tiny cross section ($\sim 0.2 \text{ fb}$), huge 4-, 6-fermion backgrounds make this among the most challenging processes to study at the LC.

Sensitivity with 1 ab^{-1} :



Detector requirements:

Excellent jet resolution

Flavor tagging

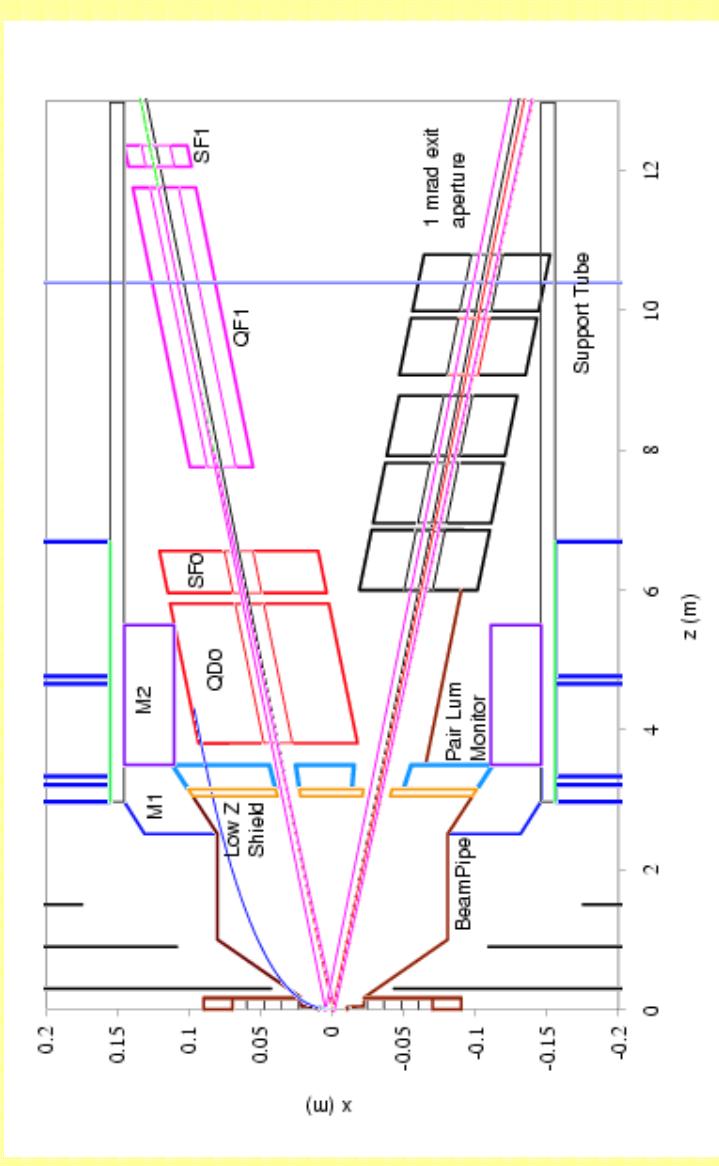
Accelerator requirements:

Lots and lots of luminosity

The Interaction Region: Where the Rubber Meets the Road

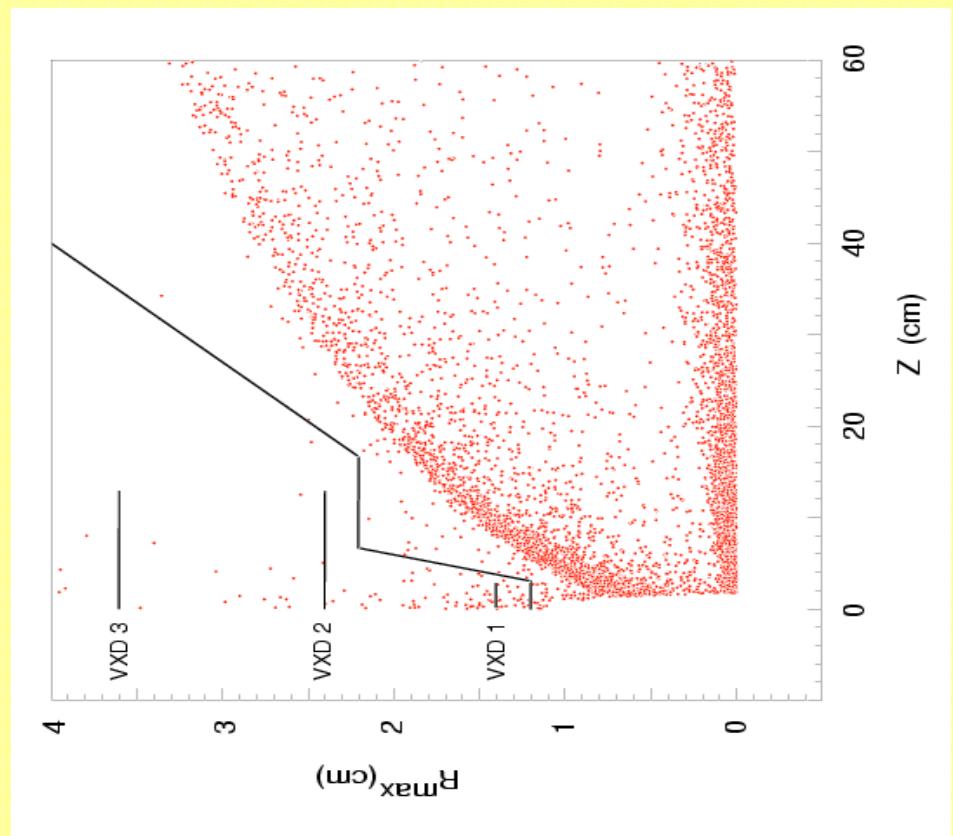
Beams collide at a 20 mrad crossing angle to avoid parasitic collisions.

Leads to effects from the solenoidal field of the detector → compensate by offsetting the final quadrupole (QD0)

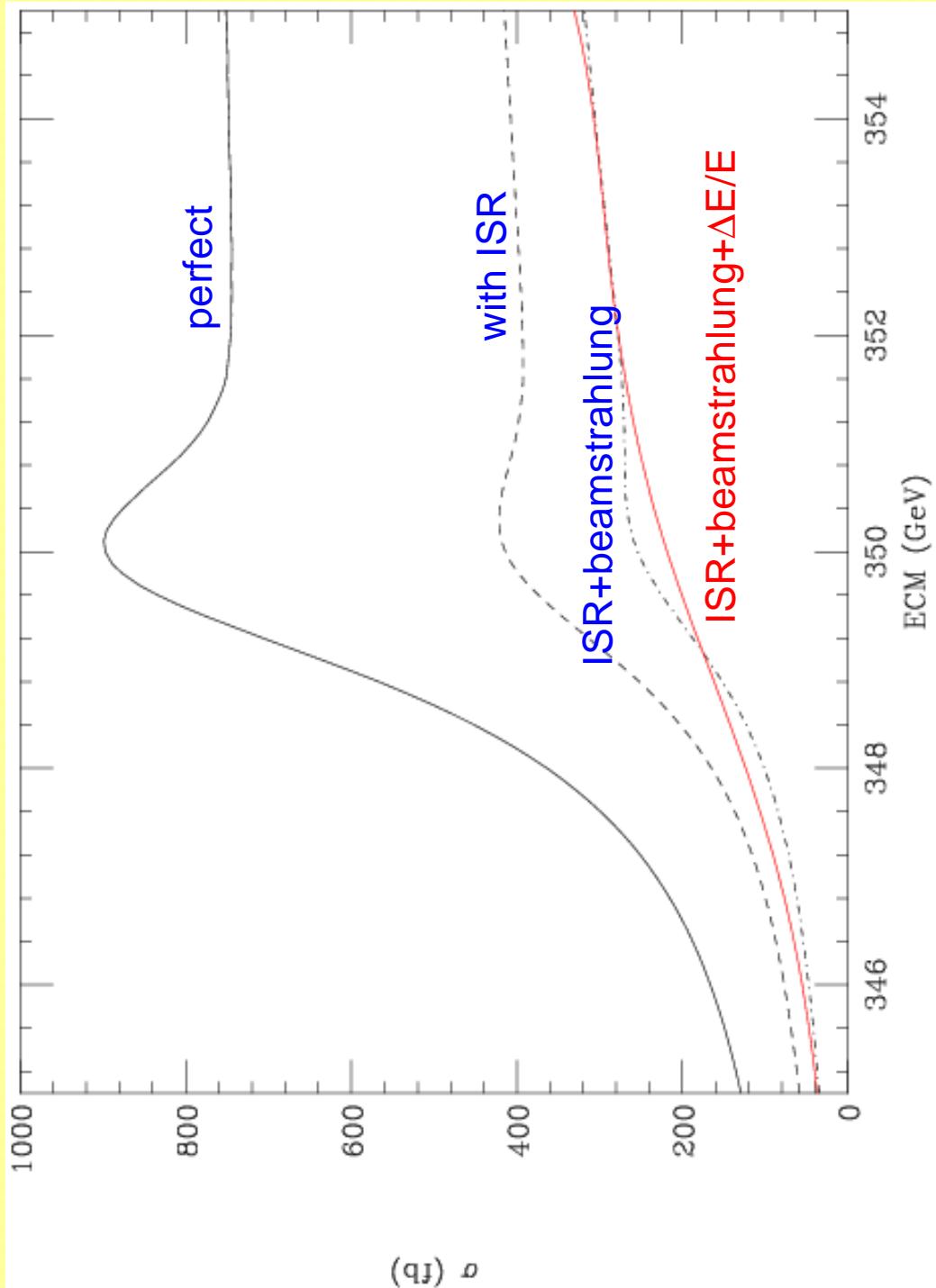


Beam–Beam Interactions

- Beamstrahlung: radiation of photons from one beam due to the field of the other beam
 - Leads to energy spread
- Production of e^+e^- pairs
 - About 10^5 per bunch, mean energy 13 GeV (~few W of power)
 - Most go into "dead cone" shown at right.
 - Drives B-field magnitude
- Other backgrounds: hadrons from $\gamma\gamma$ interactions; neutrons, muons.
- R&D question: time-stamp calorimeter and track info?



Machine Effects on Top Threshold Lineshape



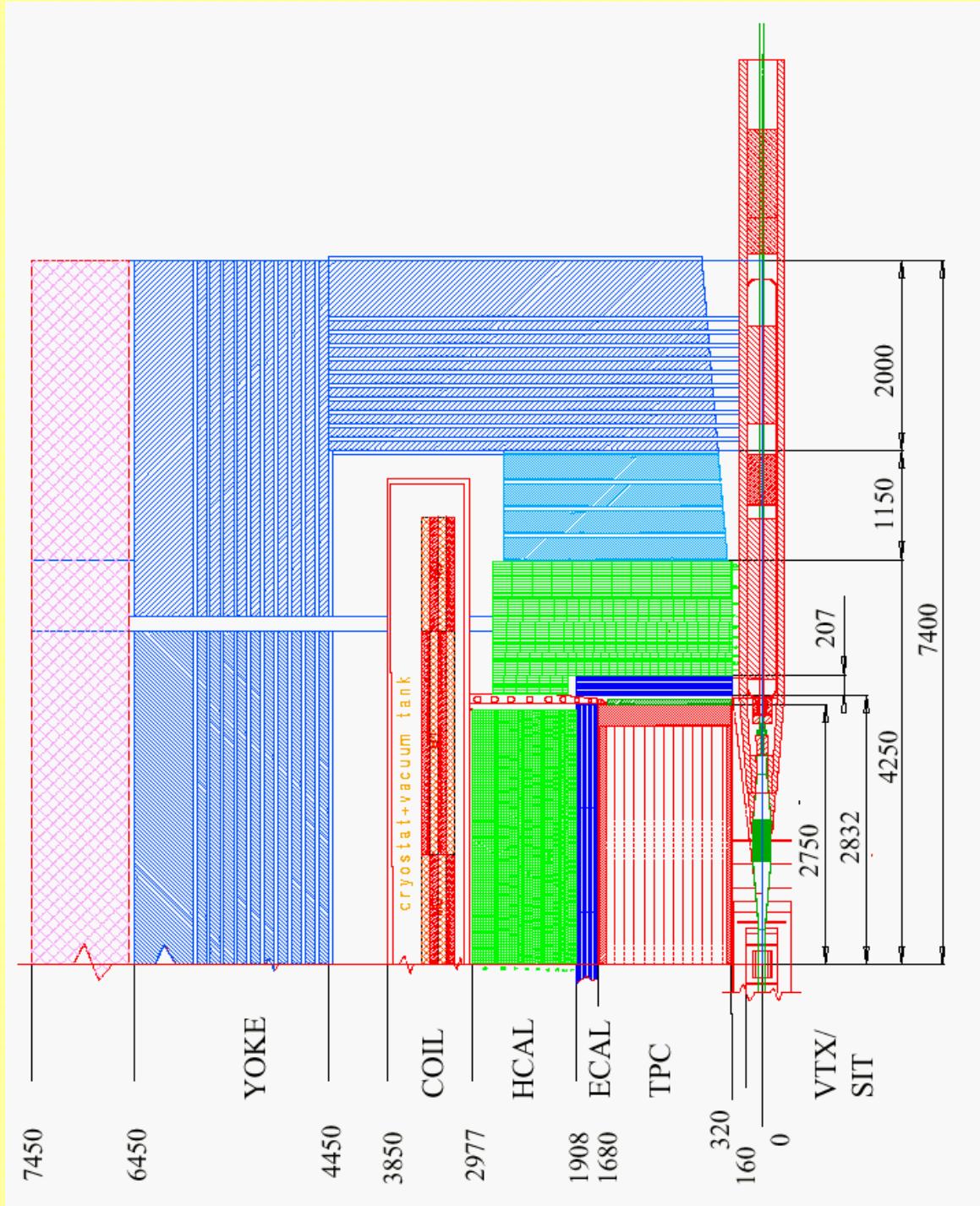
So to sum up the detector challenges, we need:

- Excellent hermeticity
- multijet final states,
forward-peaked cross sections
- Excellent calorimetry
- W/Z separation
- Excellent tracking resolution
- Precision mass measurements
- Excellent flavor-tagging
- b/c/τ identification

As opposed to a Tevatron or LHC detector
where major design drivers include:

- Ability to handle very high rates
- Radiation tolerance

TESLA Detector



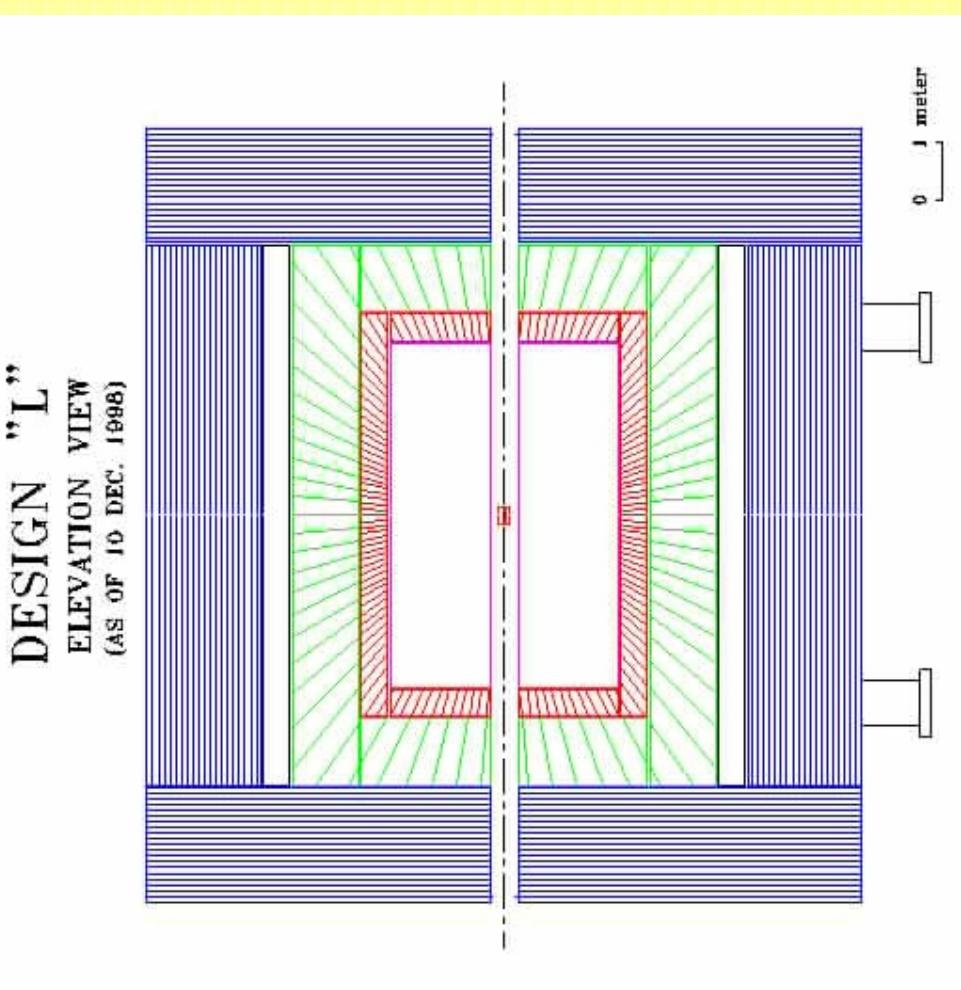
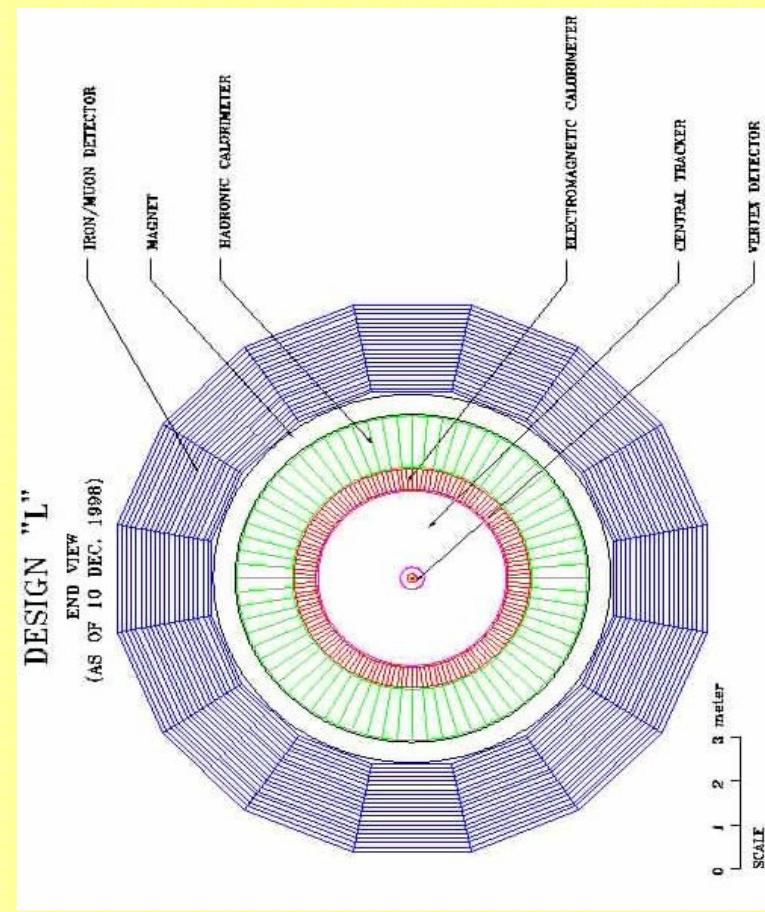
LC-LHC Detector Comparisons

	CMS	ATLAS	TESLA design
Tracker thickness (X0)	30%	28%	5%
Vertex layer thickness	1.7%	1.7%	0.06%
Vertex channel count (Mpixels)	39	100	800
ECAL granularity (det. elements)	76,000	120,000	32,000,000

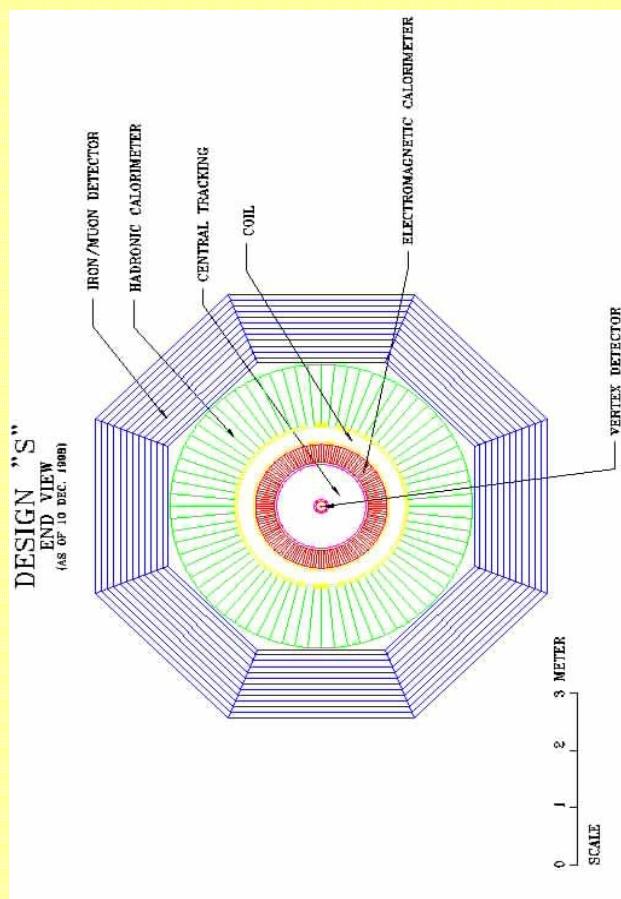
- 6x less material for photon conversions
- Vertex detector 3–6x closer to interaction point
- 35x smaller vertex detector pixel size
- 30x thinner vertex detector layers
- >200x higher ECAL granularity (*expensive*)

"A Ferrari, as opposed to a state-of-the art Abrams battle tank." (C. Damerell)

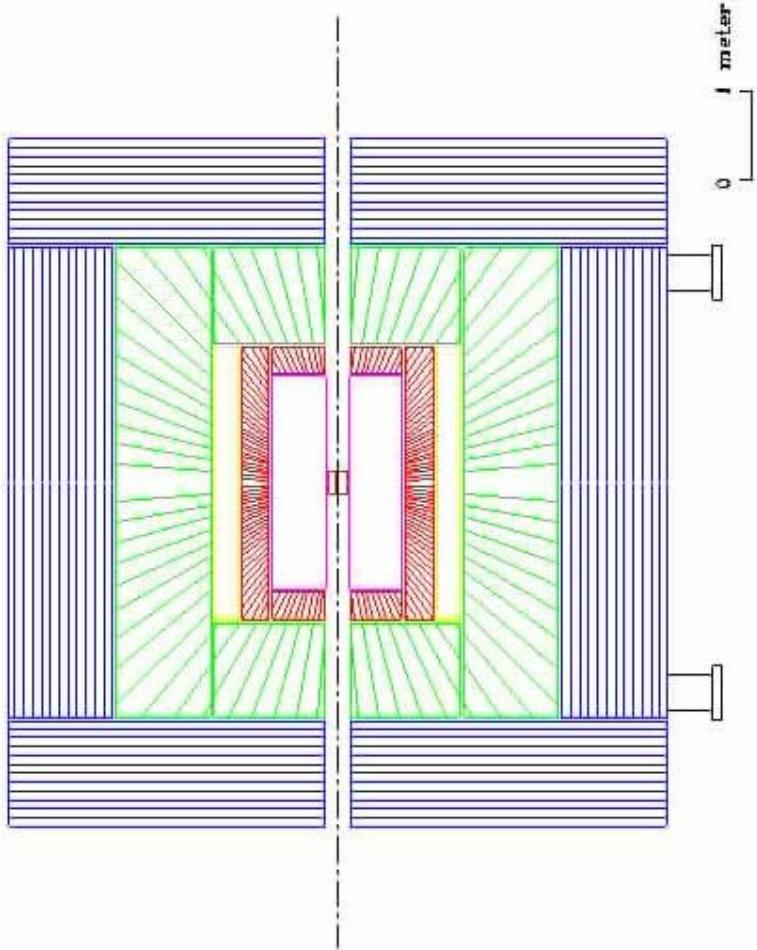
North American "Large" Detector



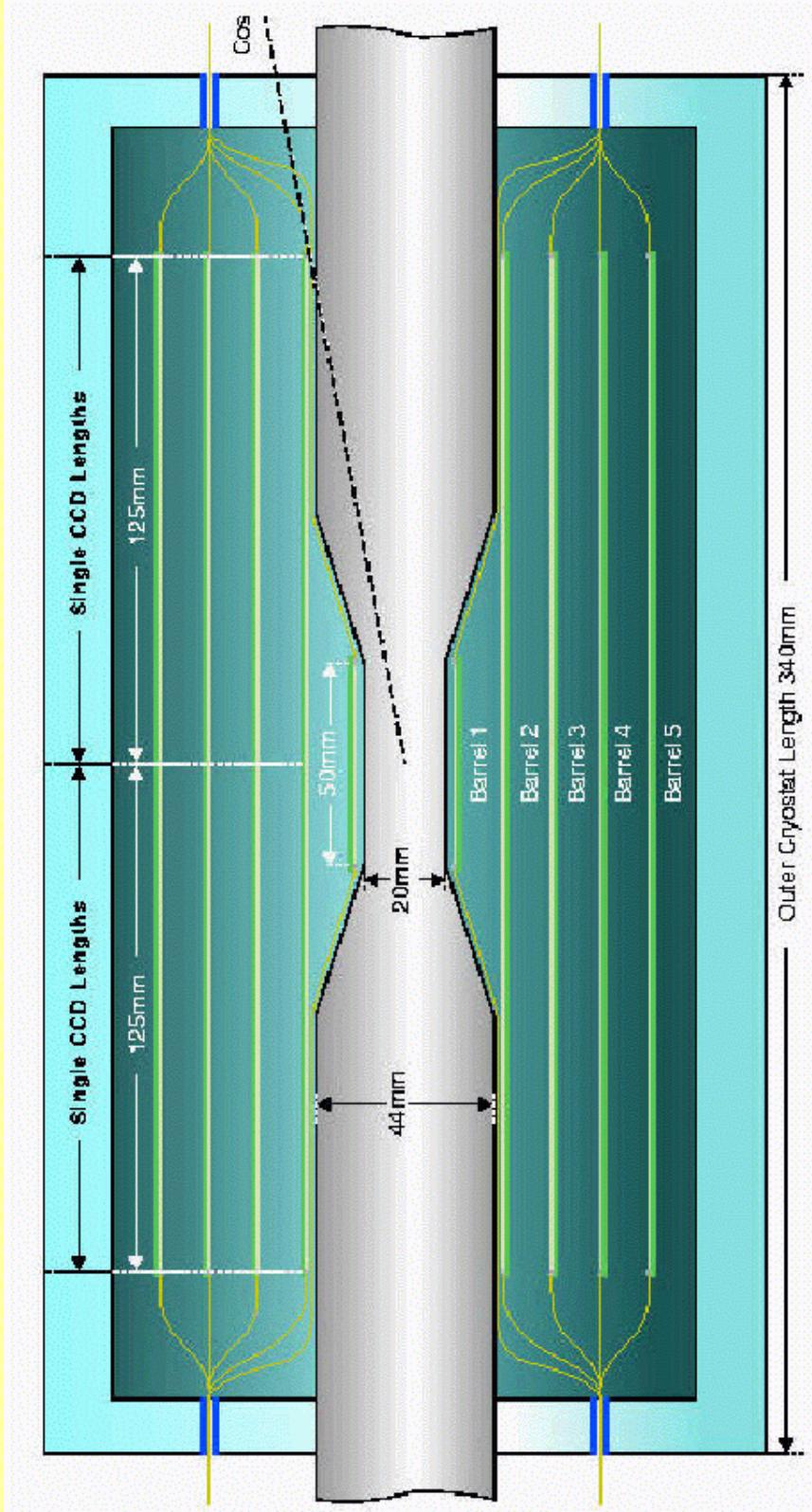
North American "Small" Detector



DESIGN "S"
ELEVATION VIEW
(AS OF 10 DEC. 1989)

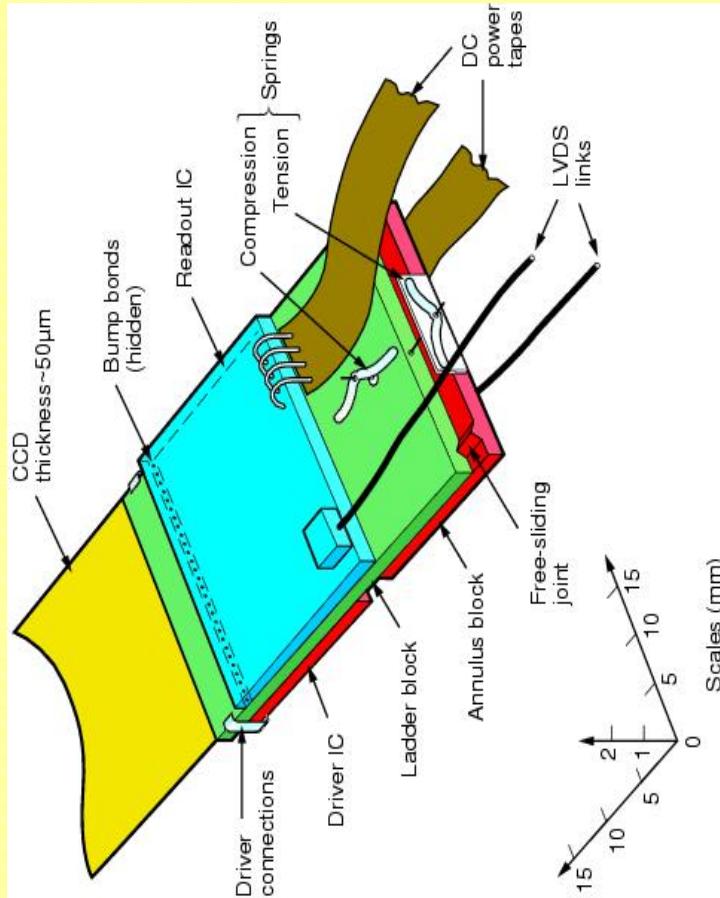
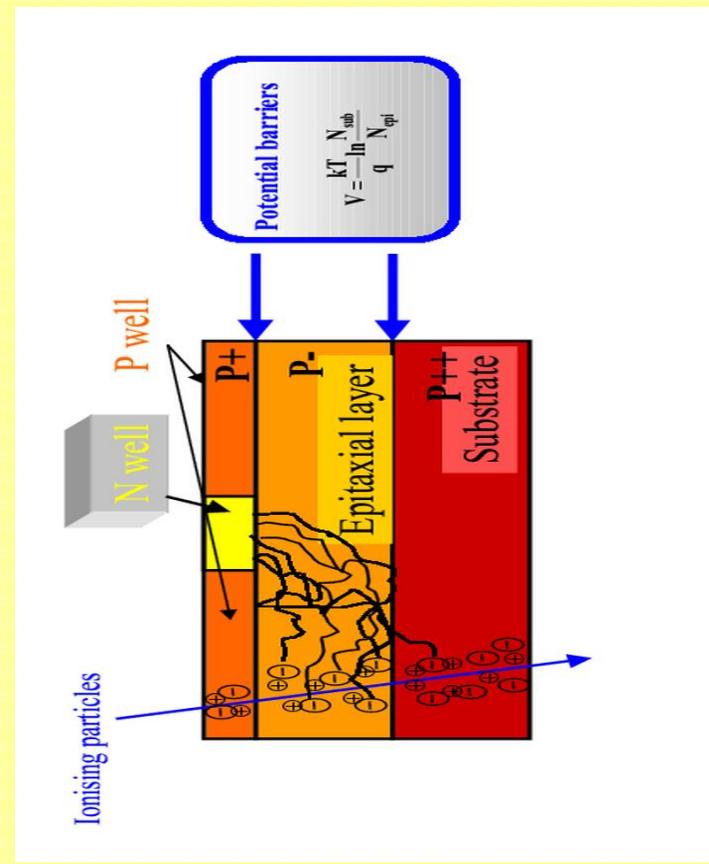


CCD Vertex Detector



Standalone 5-layer tracking device
~800,000,000 pixels
Inner layer at $r \sim 1$ cm

Pixel technology



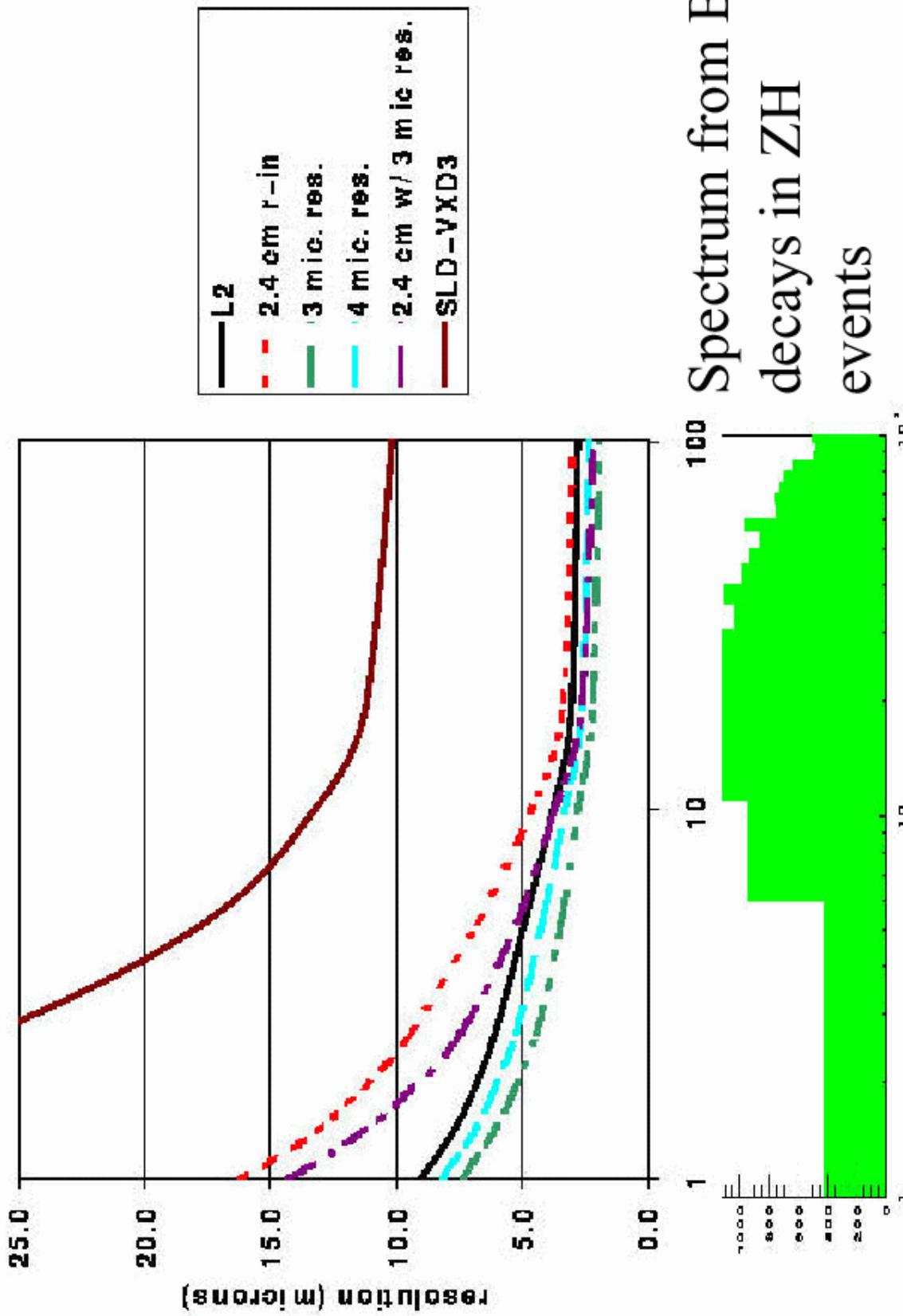
CCD pixels: the favored option, with ~3–4 μm point resolution, and least material.

Existence proof of excellent performance from SLD VXD3.

Disadvantages: Slow readout, not rad hard (enough??)

Active pixel sensors (APS): superior radiation tolerance and faster readout, but
(hybrid or monolithic) more material and worse resolution.

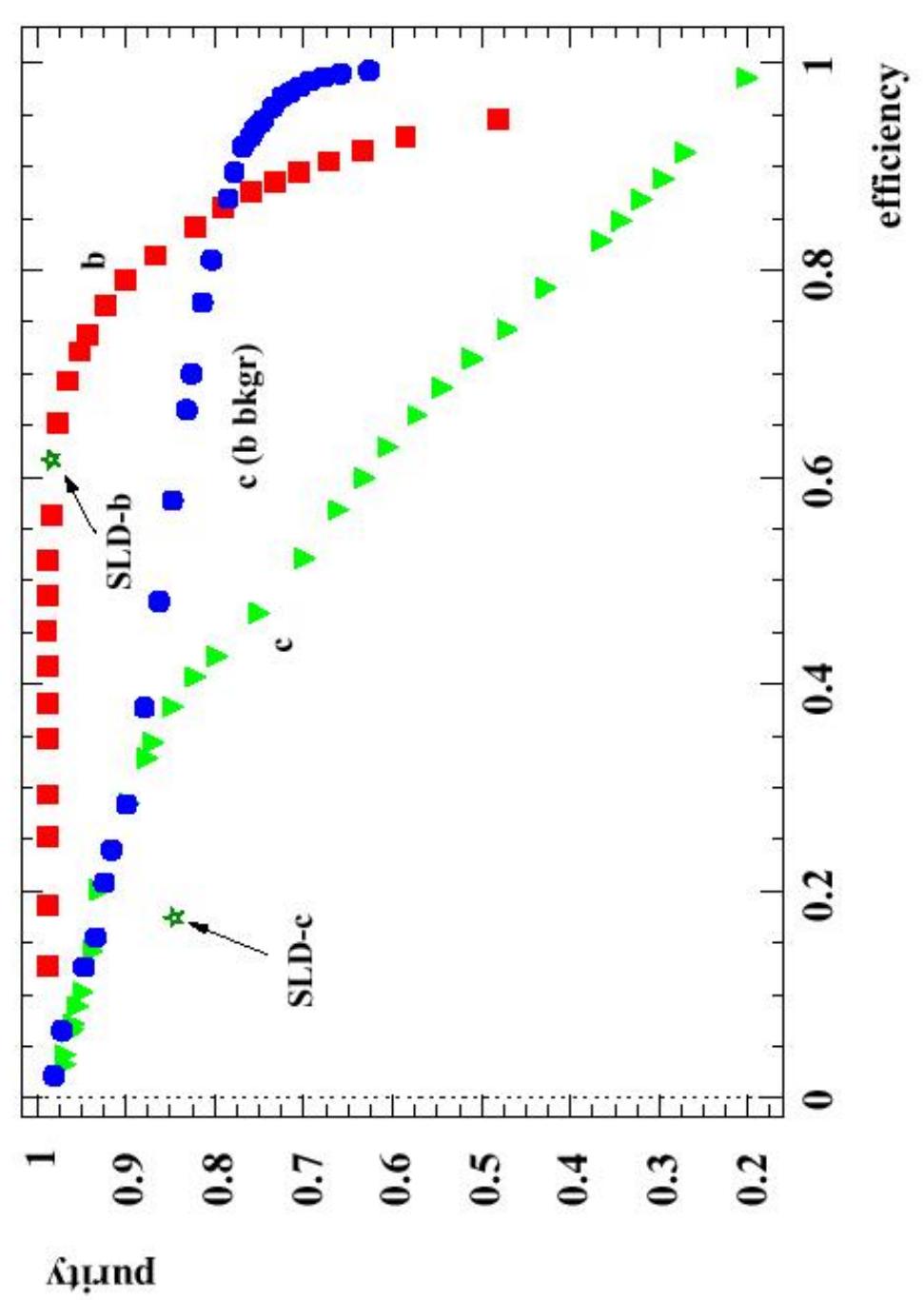
Impact parameter resolution (LCDTRK-Schumann)



R&D Issues for the VXD

- Improve rad hardness of CCD's. LC neutron backgrounds sufficiently uncertain to cause concern.
- Continued development of active pixel options.
- Better thinning of layers to reduce material
- Understand requirements for inner radius and other parameters
 - In context of global detector issues, like size and type of outer tracker, B-field strength...
- Better understanding of flavor tagging in real physics events with all backgrounds included.
- Resolve Higgs BR measurement discrepancies.
(US/TESLA studies in some disagreement)

Flavor Tagging with the VXD

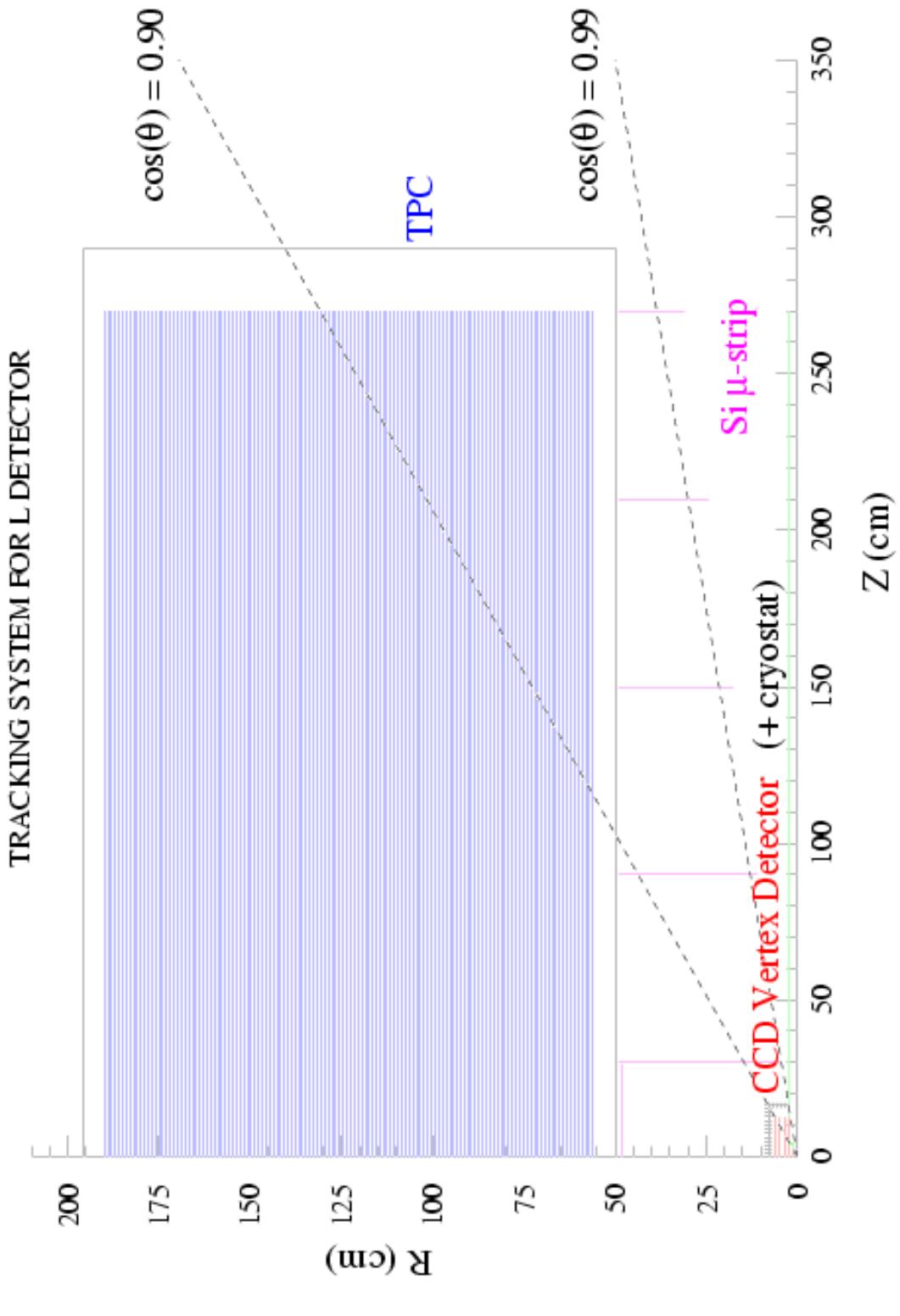


Note especially large improvement in charm tagging relative to SLD.

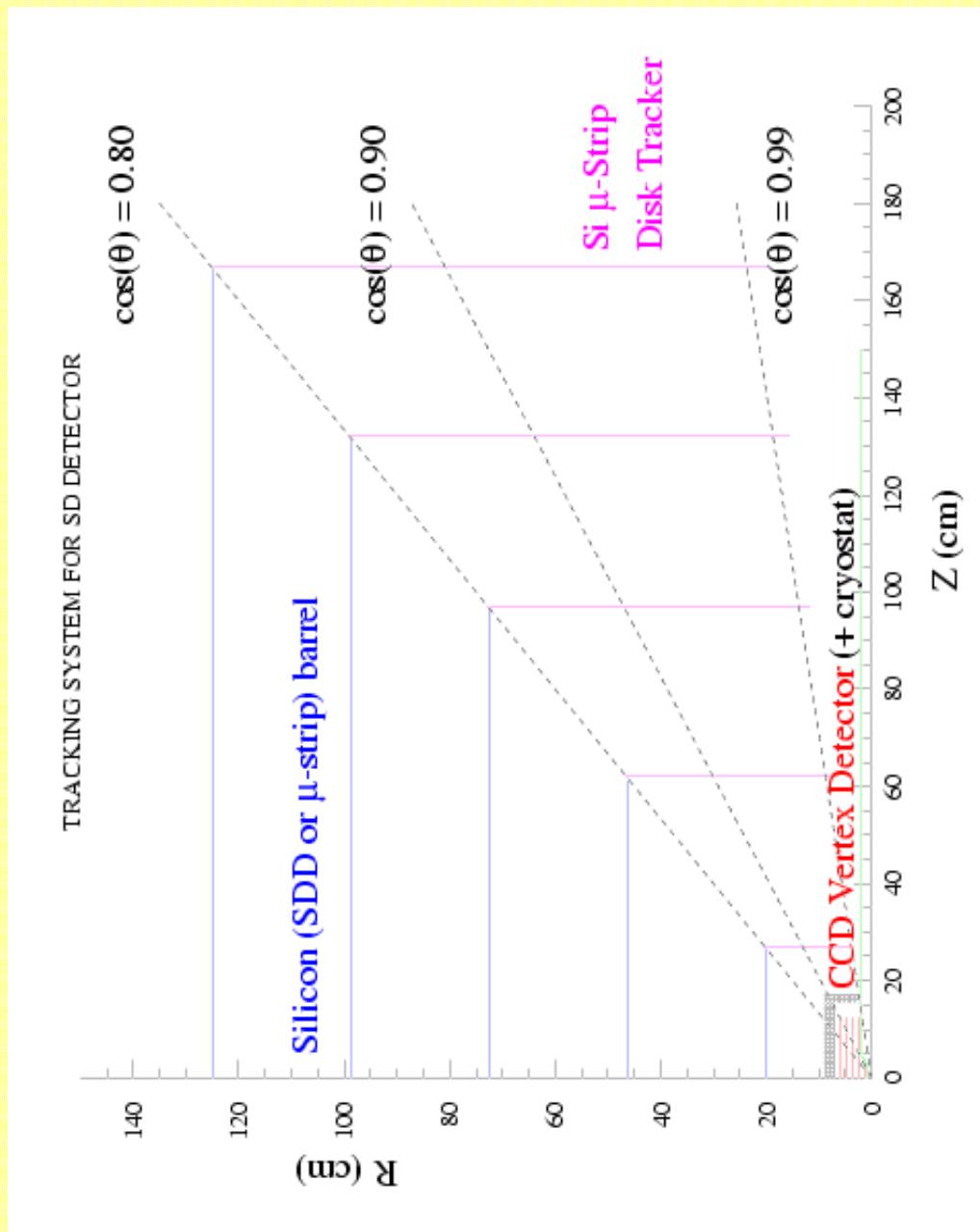
Central Tracking

- Two major designs
 - "Large" detector (TESLA detector is similar)
 - TPC tracker ($52 < R < 190$ cm)
 - 3 T B-field (TESLA uses 4 T), compare 1.4 T @ CDF
 - Forward Si disks and intermediate Si strips
 - "Small" detector
 - 5-layer Si strip or drift tracker ($20 < R < 125$ cm)
 - 5 T B-field
 - Forward Si disks
 - Optimized for "energy flow" calorimetry
- Same 5-layer VXD in both designs

"L" Detector tracking system



"S" Detector tracking system

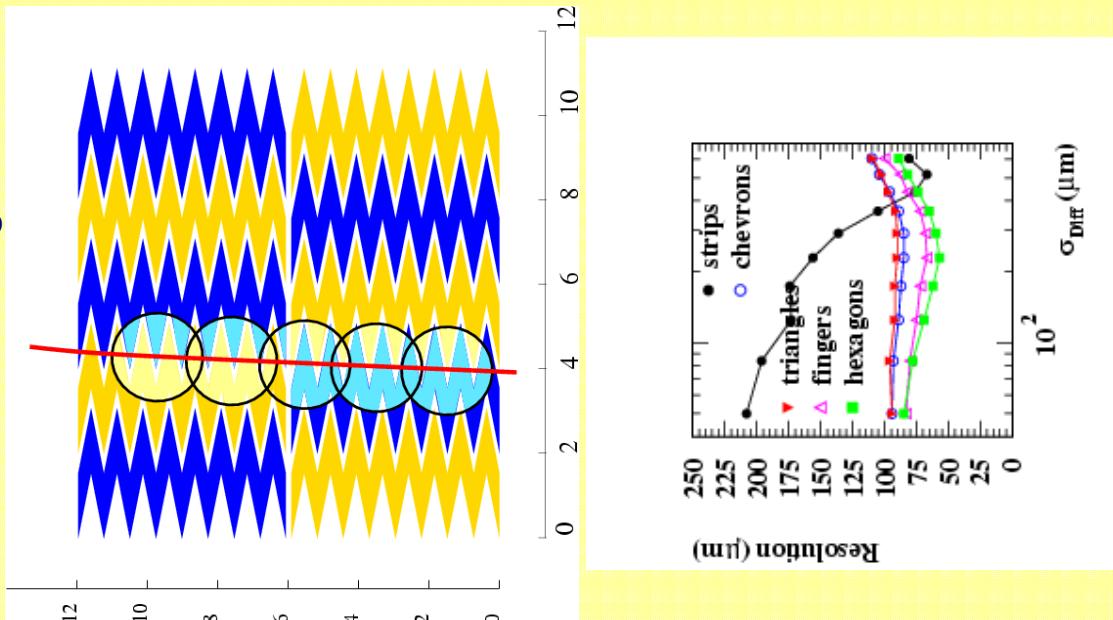
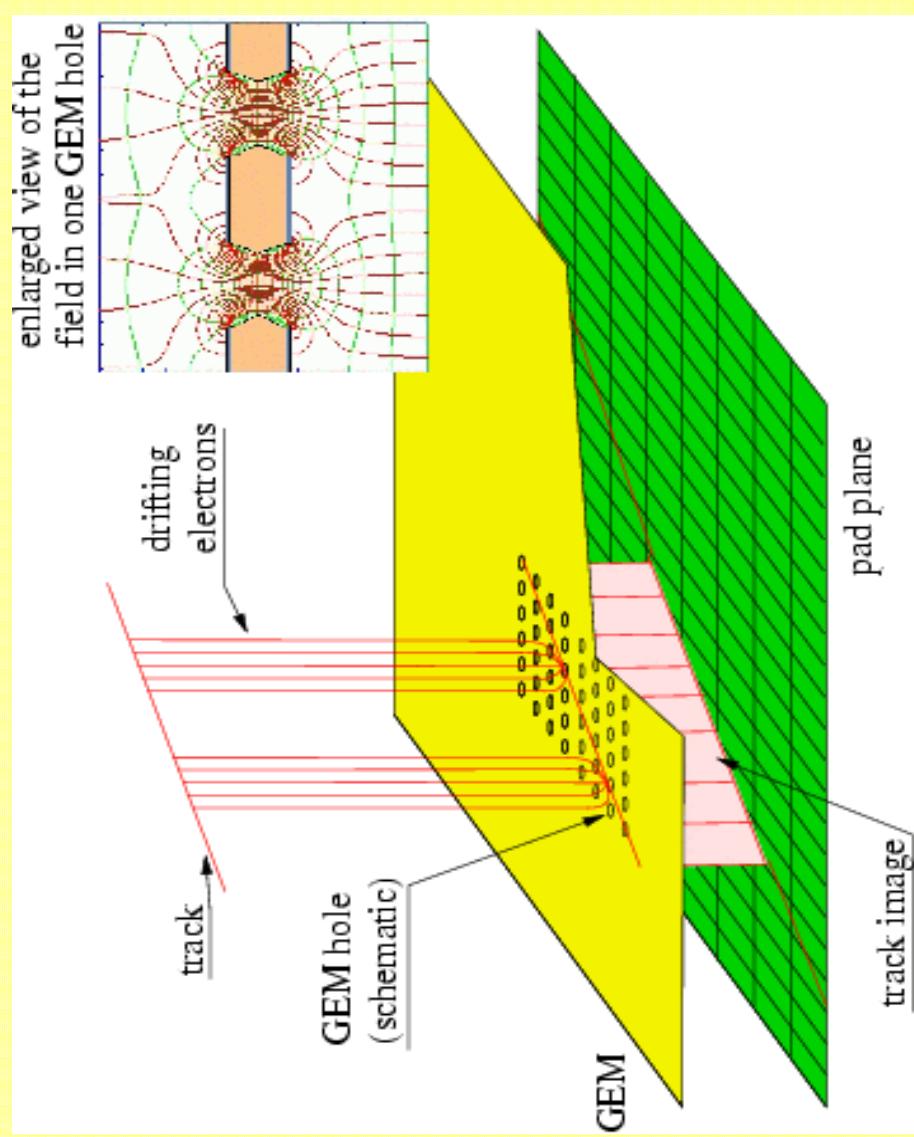


Tracking Design Issues

- Tradeoffs between a few precise hits (Si) vs. many coarse hits (gas)
 - 2-track separation, pointing accuracy
 - Robustness of pattern recognition against backgrounds
 - Get dE/dx in a gas tracker "for free". Is it necessary?
- 3D devices (TPC or Si drift) vs. 2D (drift chamber or Si strips)
- Need an intermediate tracker if a gas outer tracker is chosen?
 - Depends on R_{\max} of VXD and R_{\min} of outer tracker.
 - May improve momentum resolution by factor of 2.
 - Effect on pattern recognition unclear.
 - May provide a means to tag bunch-ID

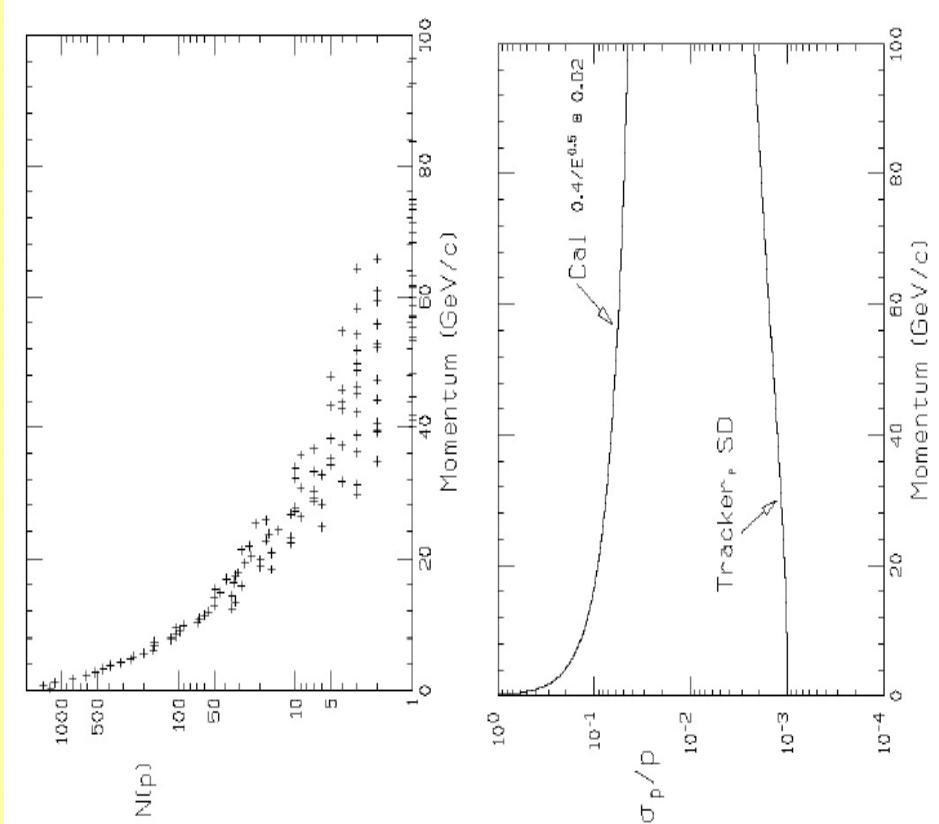
Much R&D on TPC readout technology, such as **GEM** and **Micromegas**

Resolution depends on pad shape, e.g. see improvement with "chevron" design.



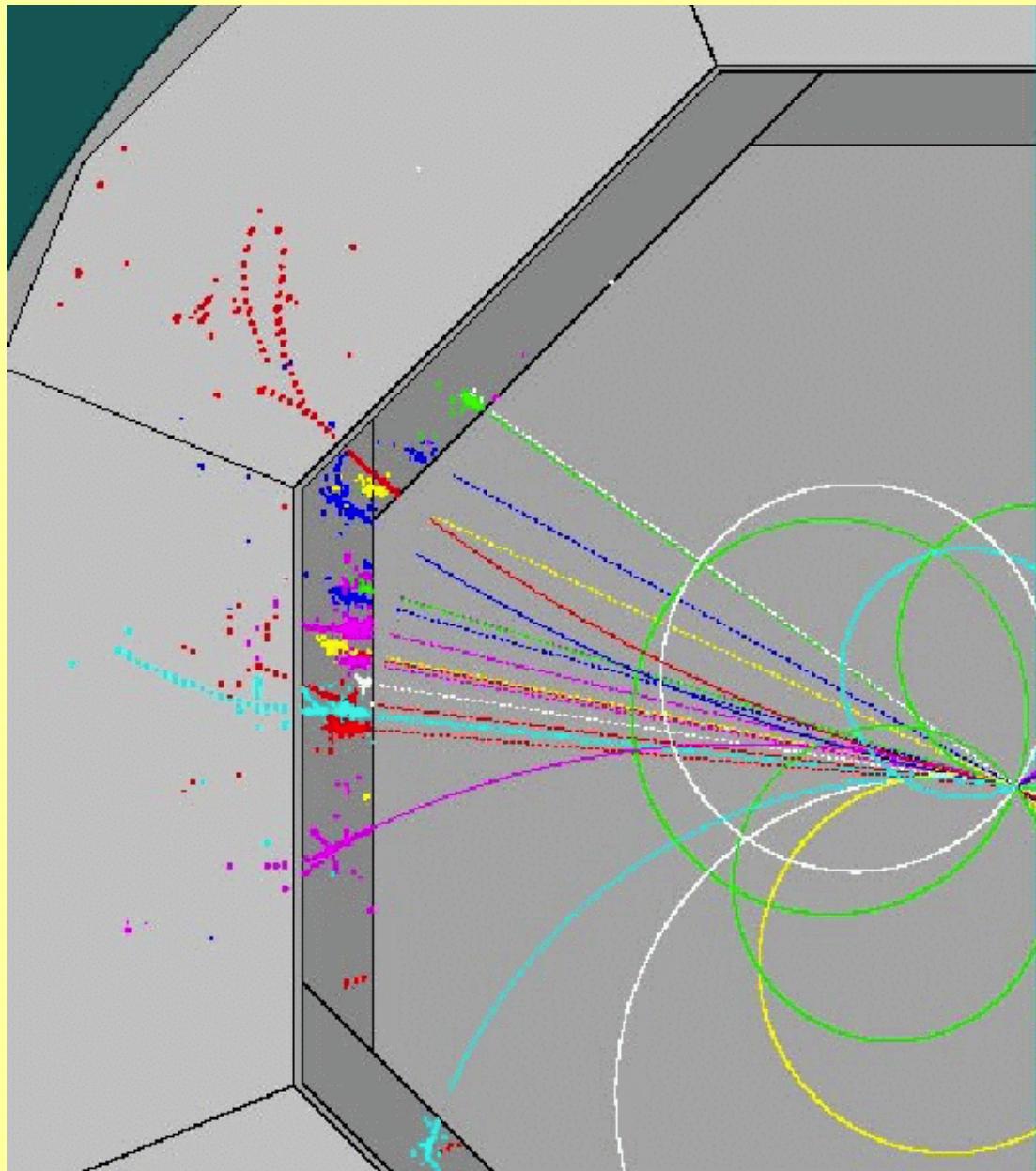
Calorimetry: The Energy–Flow Concept

- Typical jet contains:
 - 64% charged energy
 - 25% photons
 - 11% neutral hadrons
- Main idea: use tracker for charged particles, calorimeter for neutrals only:
$$E_{\text{jet}} = \sum p_{\text{charged}} + \sum E_{\text{neut,ECAL}} + \sum E_{\text{neut,HCAL}}$$
- Requires a very finely segmented calorimeter so that one can extrapolate tracks to charged particle energy and remove it.
 - Figure of merit is BR^2/R_m
 - Fine segmentation = high channel count = high cost. How good is good enough?



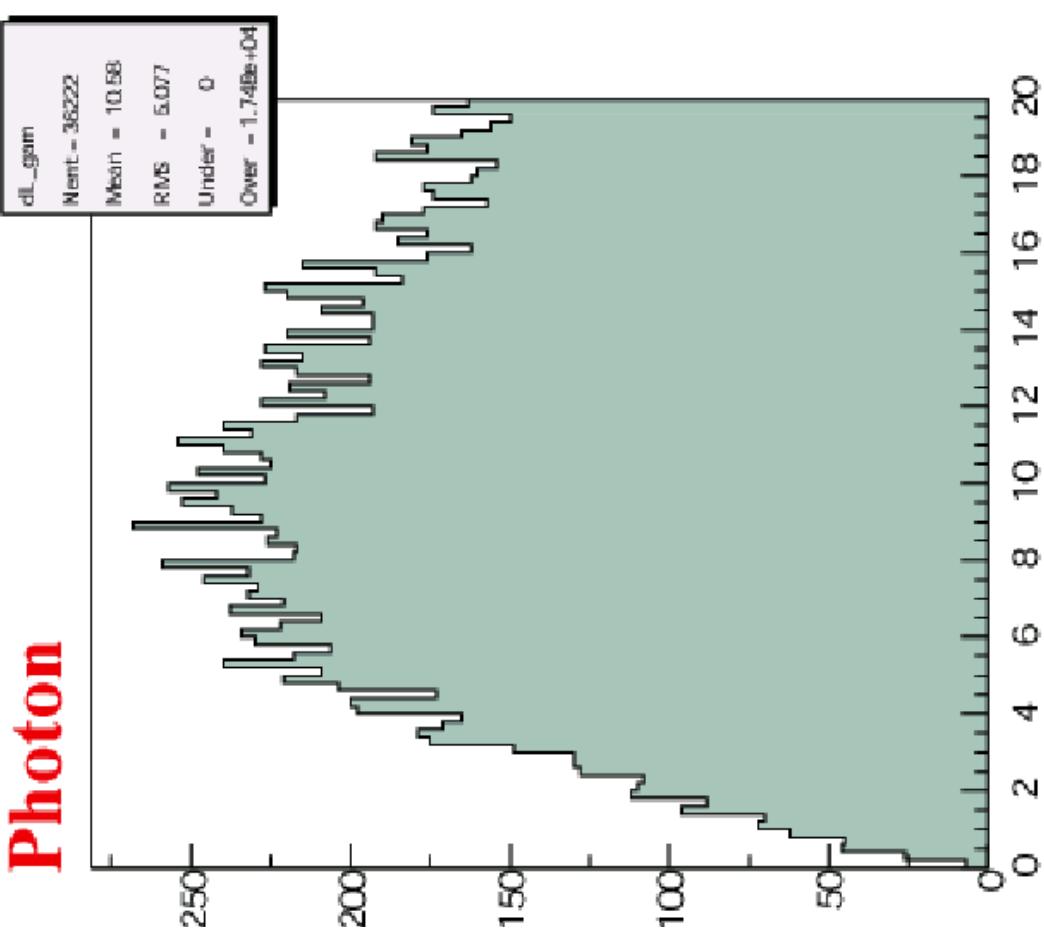
R. Frey, Chicago LCDW '02

Energy Flow at TESLA

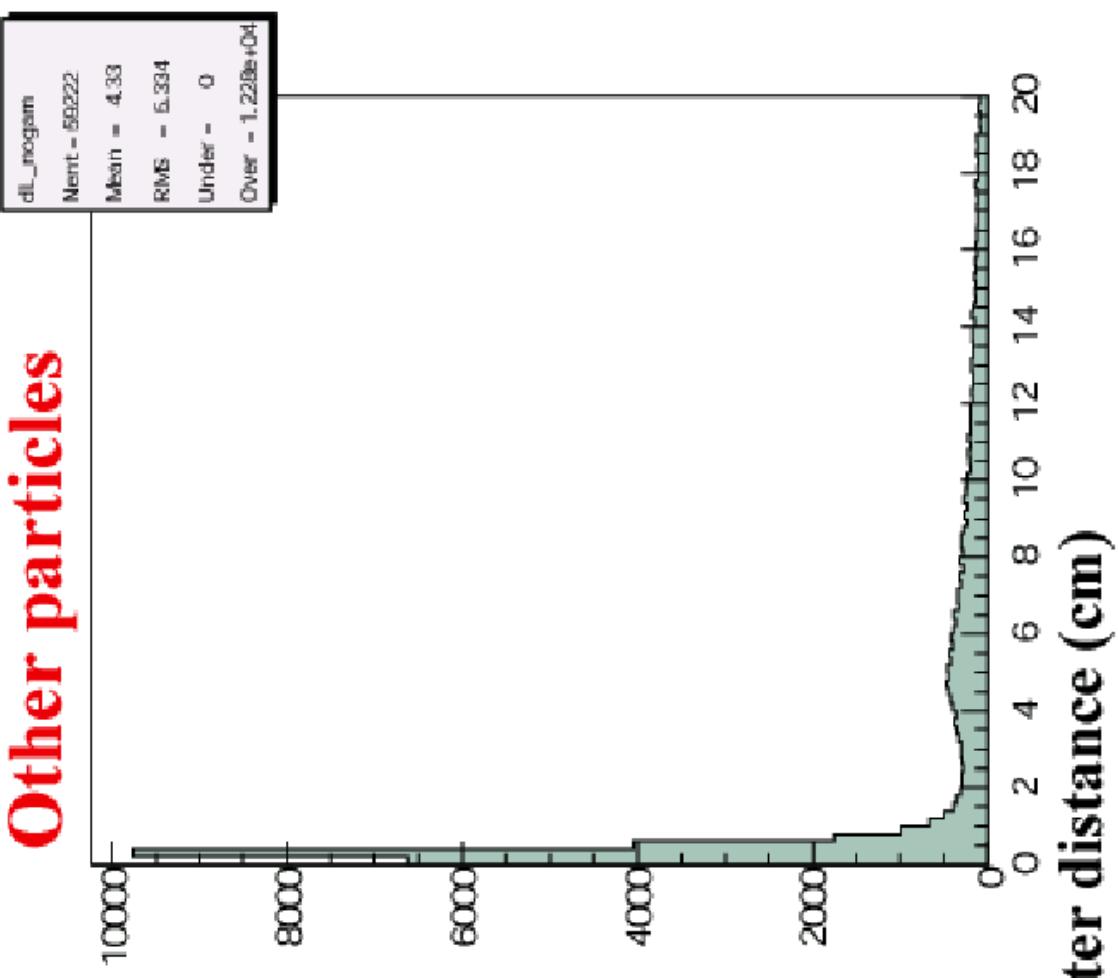


Perform photon ID by looking at distance between track and nearest EM cluster in "S" detector design

Photon



Other particles

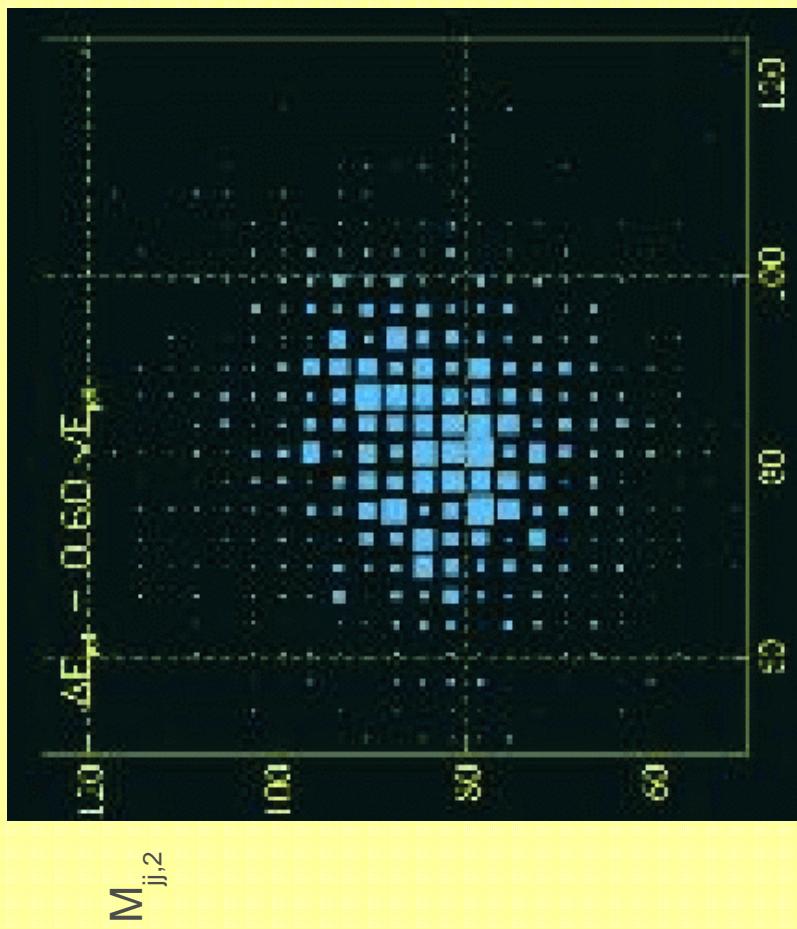


Benefits: Better Jet Resolution

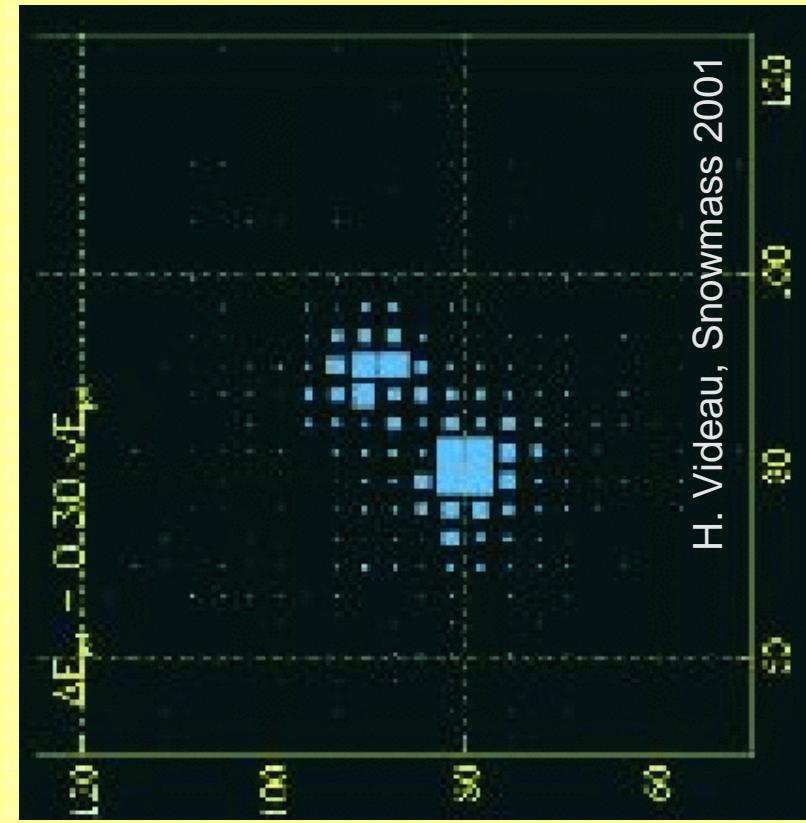
Separation of $e^+e^- \rightarrow W\bar{W}vv$ from $e^+e^- \rightarrow ZZvv$:

$$\Delta E/E = 0.6/\sqrt{E}$$

$$\Delta E/E = 0.3/\sqrt{E}$$

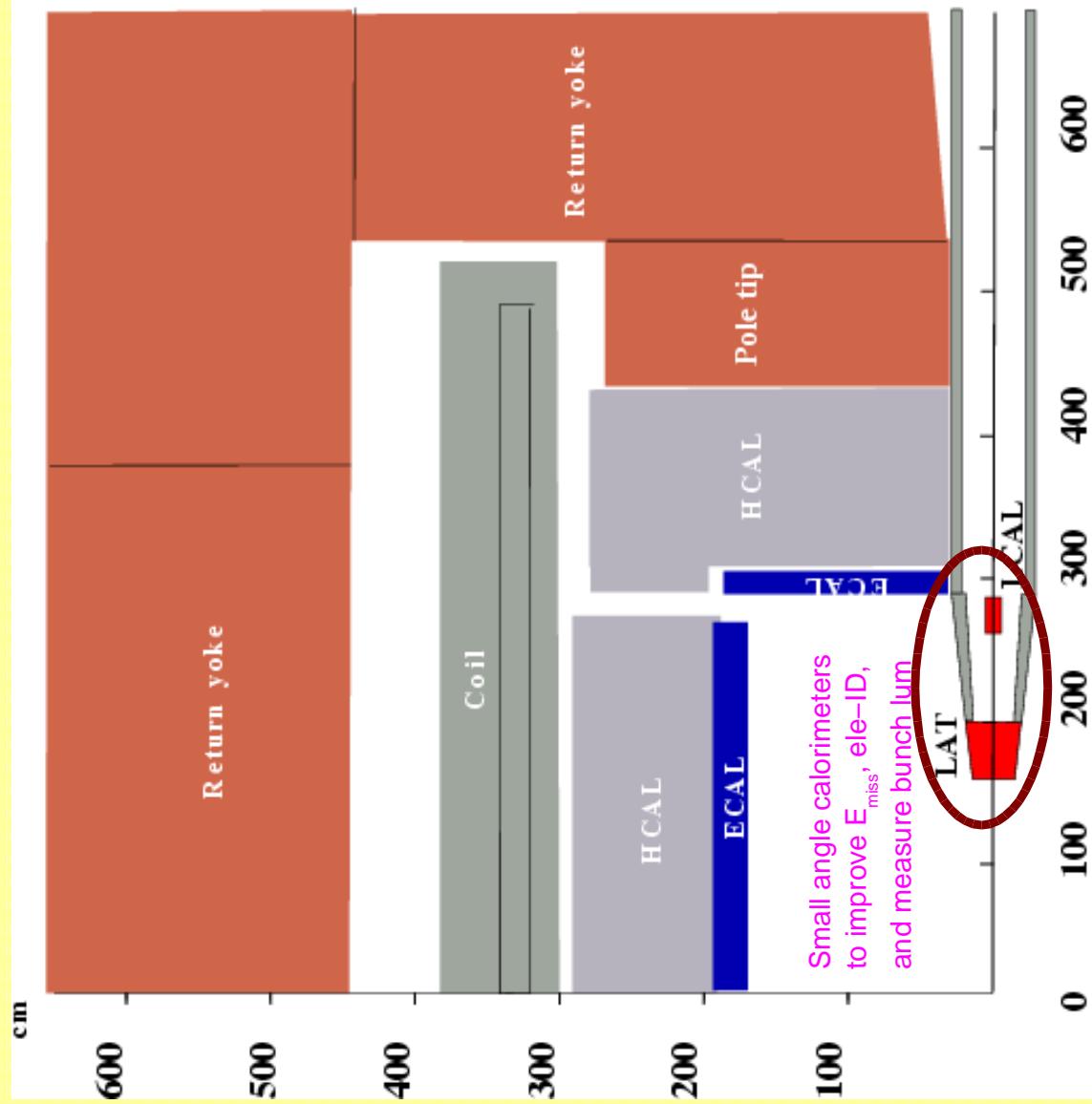


$M_{jj,1}$



$M_{jj,1}$

TESLA Calorimeter



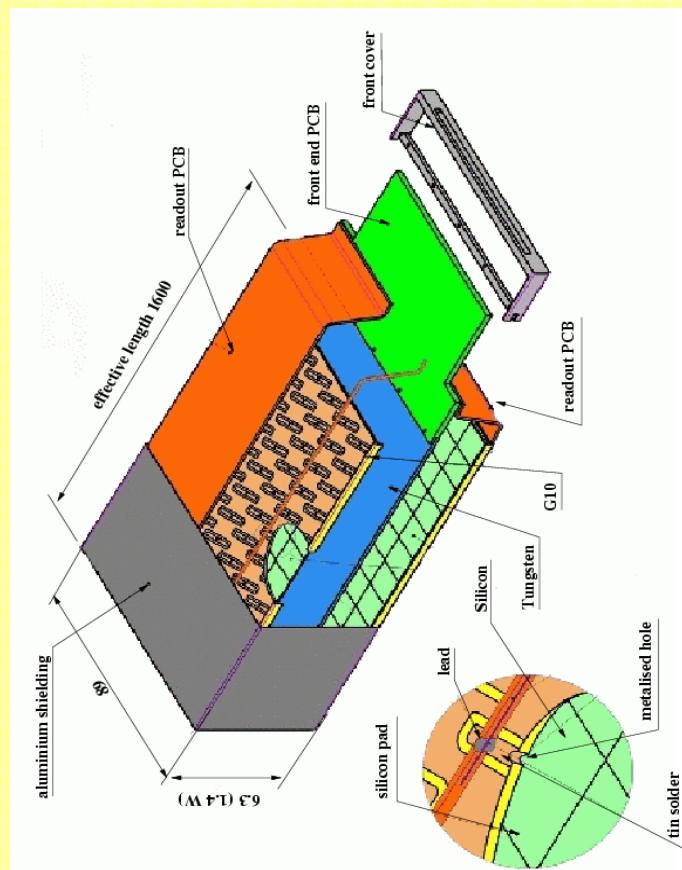
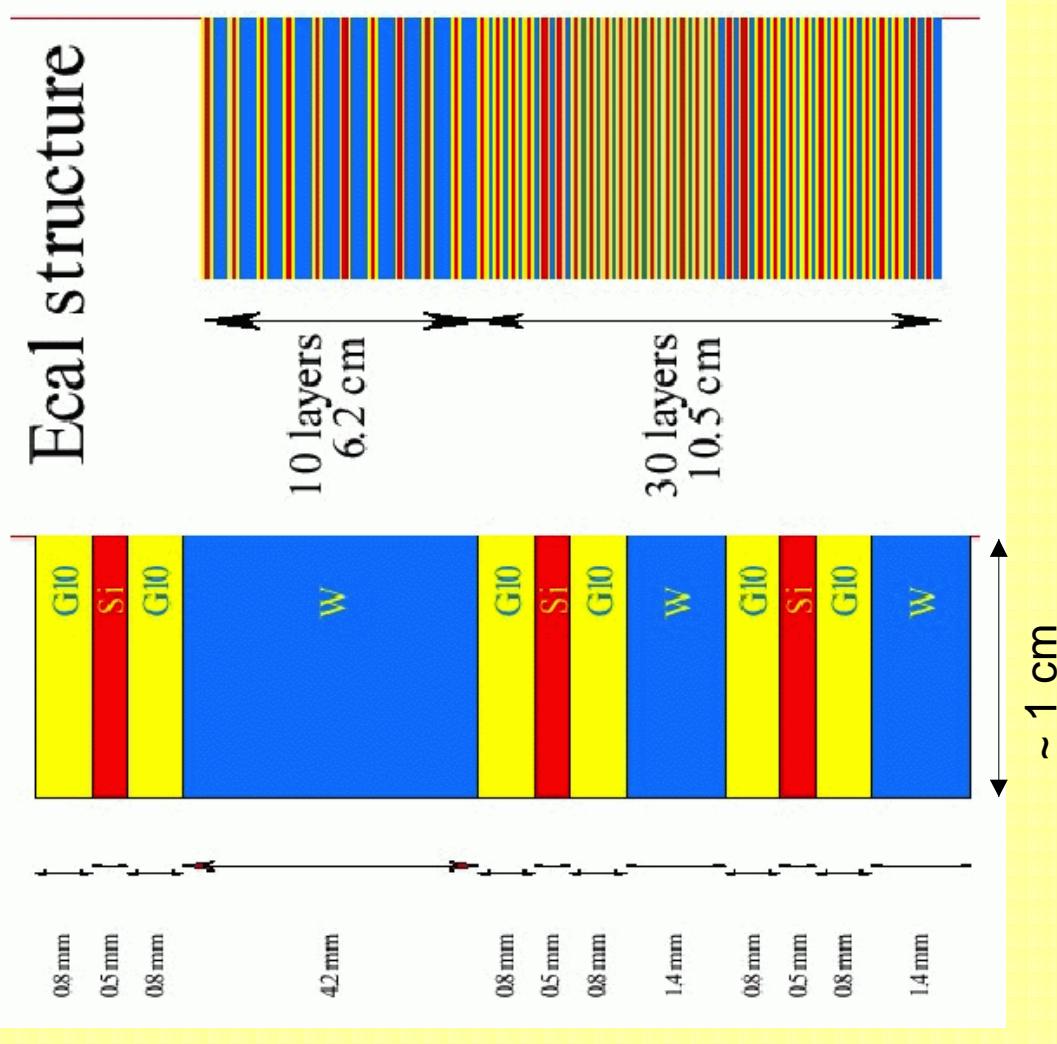
W/Si EM Calorimeter

- 30 layers of $0.4 X_0$ tungsten absorbers
- 10 layers of $1.2 X_0$ tungsten
- 1 cm^2 segmentation
- 32 million channels
- Cost about 133 Meur, dominated by $\sim 3000 \text{ m}^2$ of Si wafer

Two HCAL Options:

- Digital, 1 cm^2 pad size using RPC's
- Scintillating tile, 5 cm^2 segmentation

Ecal structure



Calorimeter Comparisons

S detector

- Optimized for energy flow
- $BR^2/R_m \sim 5$ (like TESLA)
- W/Si ECAL

- $5 \times 5 \text{ mm}^2$ transverse segmentation
- 2.5 mm sampling ($0.71 X_0$)
- $\sim 1000 \text{ m}^2$ Si (more compact than TESLA)

Granular HCAL

- 1 cm^2 segmentation (RPC's, scint?)
- 5λ depth

L detector

- $BR^2/R_m \sim 6$ (good)
- But segmentation too coarse for E-flow? (bad)
- Pb/Scint ECAL
 - $5 \times 5 \text{ cm}^2$ transverse segmentation
 - 4 mm Pb / 1 mm scint long. seg.
 - $R_m \sim 20 \text{ mm}$
- Pb/Scint HCAL
 - $20 \times 20 \text{ cm}^2$ tiles
 - 8 mm Pb / 2 mm scint
 - 7λ depth

Calorimeter R&D Issues

- Further develop physics justification for excellent energy flow
W/Z separation at high energy, $t\bar{t}H$, Higgs self-coupling, SUSY, heavy Higgs?
- Detailed simulation of energy flow; integration with flavor tagging
- Parametrize for fast simulation / refine based on detailed simulation
- Can we use the calorimeter as a muon tracker?
- Physics case for non-pointing photons (SUSY...)
- Parameter tradeoffs: trans/long segmentation, B-field size,
calorimeter radius, coil location.
- Less expensive alternatives to Si/W? (e.g. scint. tile?)
- What if we can achieve high B-fields, i.e. 5 T?

Conclusions / What you should do now

- The LC has a vital role to play in our understanding of the TeV scale.
- Sooner or later it is going to happen, somewhere...
- What you should do if you are a Tevatron grad student or postdoc:
 - Educate yourself, as you are doing here today.
 - Keep working hard on your experiment!
 - The strongest case for the LC may come from discoveries that you will make here at Fermilab!

Acknowledgements

I have told you about a large amount of work on both physics and detectors, most of which has been done by other people. For this talk I am indebted to material from:

Jim Brau, Chris Damerell, Ray Frey, Masako Iwasaki, Tom Markiewicz, Keith Riles, Bruce Schumm...

... and the hundreds of participants in the Worldwide Study of the Physics and Detectors for Future e^+e^- Linear Colliders.

To learn more:

- The TESLA TDR: tesla.desy.de/TDR_CD/start.html
- Linear Collider Resource Book: slac.stanford.edu/grp/th/LCBook